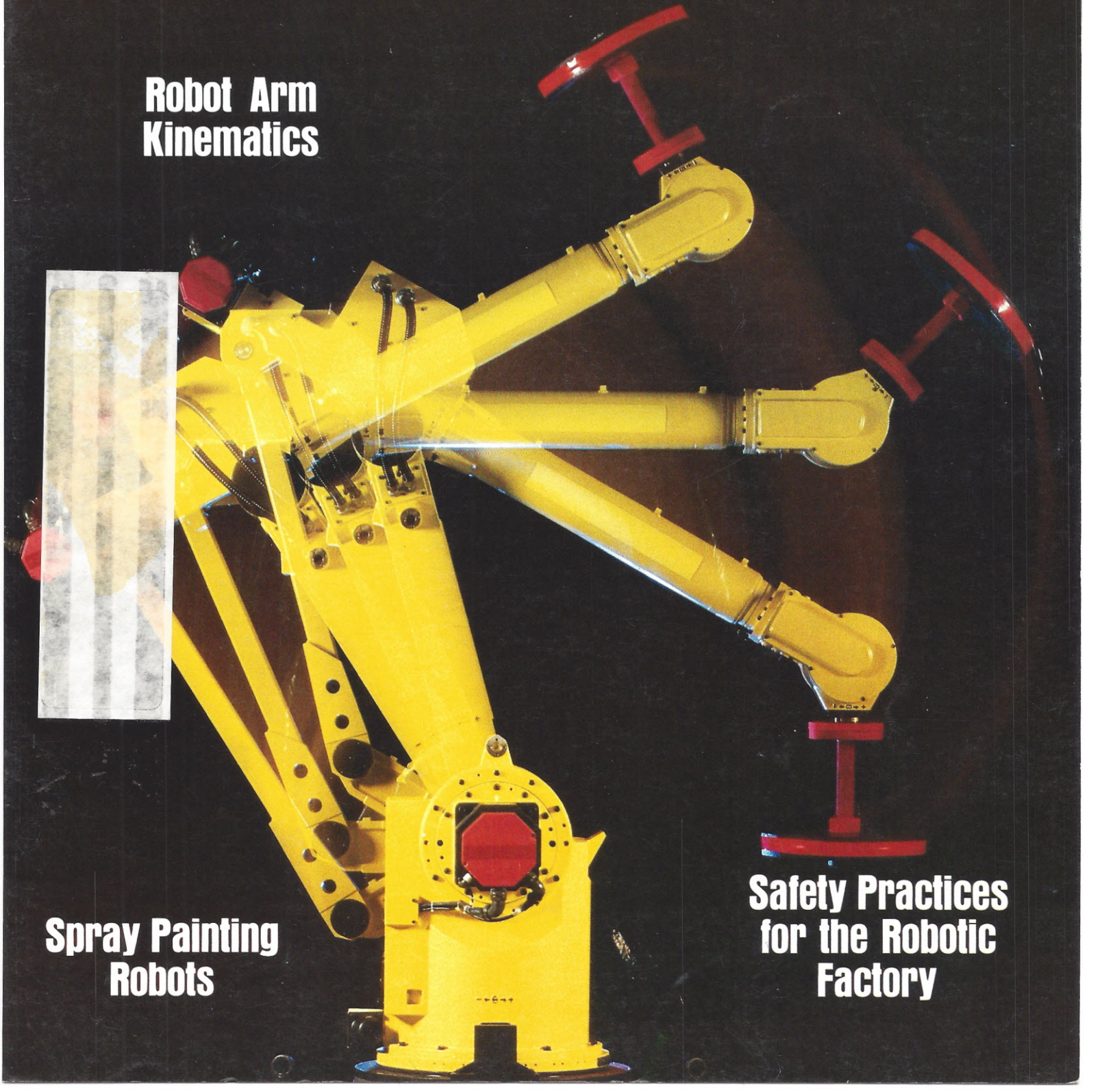
JULY 1986 VOL. 8 NO. 7

$3.00 USA/$3.50 CANADA

ROBOTICS ENGINEERING

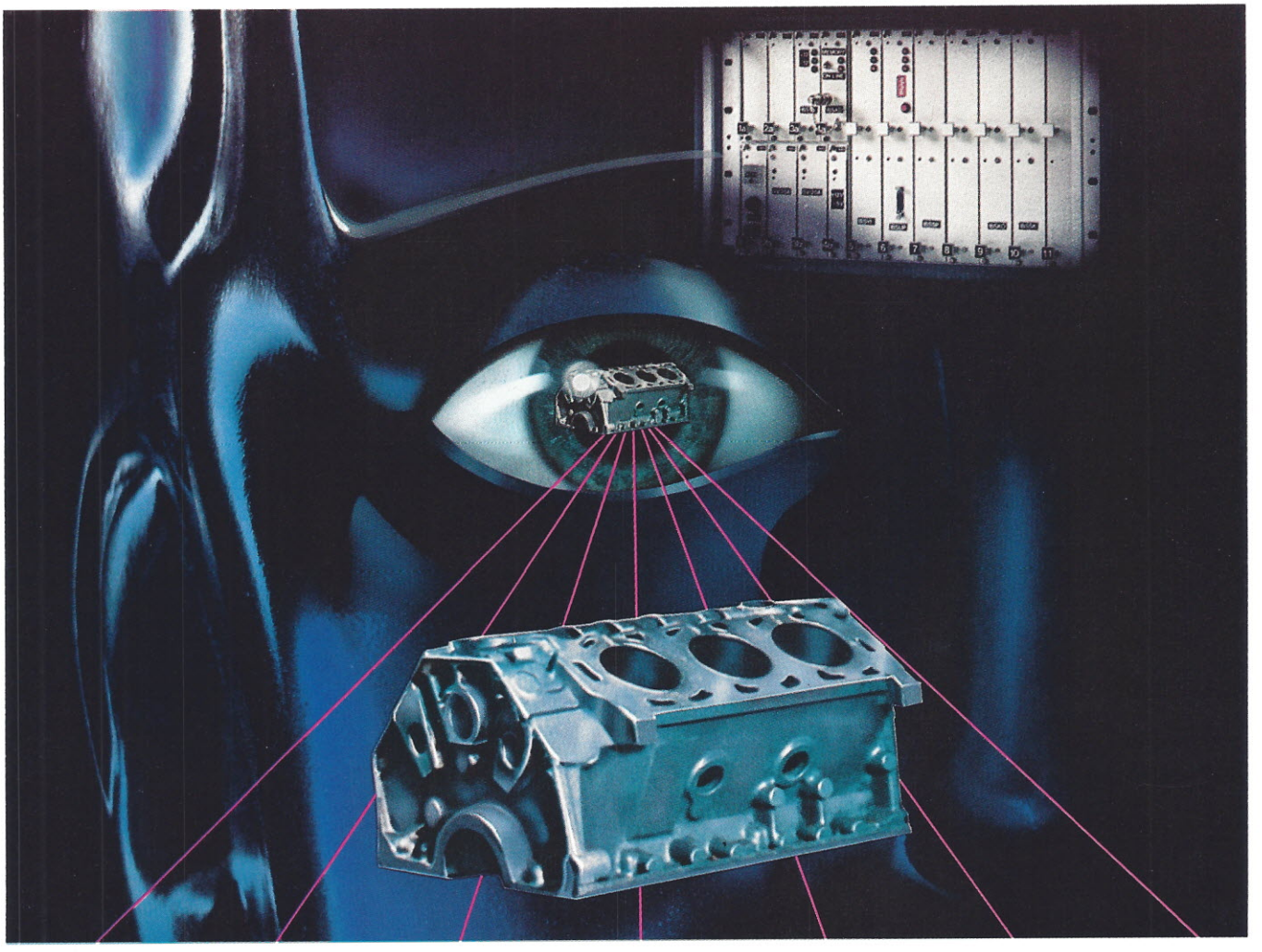
THE JOURNAL OF INTELLIGENT MACHINES

Robot Arm Kinematics



Spray Painting Robots

Safety Practices for the Robotic Factory



Multiprocessor based robotics controllers with integrated PLC; robot guidance and vision systems ...that's high technology from AEG!

AEG believes that industrial automation should be simple, reliable, flexible and easy to operate. Our technology has made that belief a reality with the R-500 programmable robot controller.

The R-500 is a modular, distributive, multiprocessor based system which provides high speed computing power while remaining completely user friendly through its English text programming. The design includes linear and rotational motion control, vision systems interfaces and communications capabilities such as LAN, MAP and others.

This system provides a built-in integrated programmable logic controller (PLC) which eliminates the need for separate PCs and effectively provides total control of the workcell.

Our industrial vision system operates much like the human eye in that the camera is the functional equivalent of that organ which "sees" products on the line in gray-scale. Pre-processing is handled by the electronic interface while the vision controller, which is high speed multiprocessor based, performs the decision making processes. AEG firmware supports applications such as part recognition, inspection tasks and robot guidance.

AEG is a worldwide source for technological innovation in areas which include not only robotics but, information systems, satellites, solar power, electronic packaging, power semiconductors, technical tubes and office systems.

For more information on our vision system and programmable robot controllers contact our Detroit office:

AEG Corporation
17177 North Laurel Park Drive
Livonia, MI 48152
(313) 591-2233.

For more information on our other high technology products contact our corporate headquarters:

AEG Corporation
Route 22-Orr Drive
PO Box 3800
Somerville, NJ 08876-1269
or call (201) 722-9800.

AEG

Circle 48

Publisher
Chris Crocker

Editor
Carl T. Helmers, Jr.

Associate Editor
Stephanie vL Henkel

Consulting Editors
Rakesh Mahajan
Robert E. Parkin, Ph.D.
Roberta Toth

Editorial Coordinator
Lorraine Cleveland

Production/Design Director
David Wozmak

Production Assistant
Ruth S. Wilder

Typography
Sheryl Fletcher

Circulation Manager
James E. Bingham

Circulation Assistants
Jim Pelletier
Winnie Werth

Receptionist
Deborah Louzier

Advertising Manager
Donna Louzier

Advertising Coordinator
Meredith Bickford

Advertising Sales

Midwest:

Don Ransdell
The Pattis Group
4761 West Touhy Ave.
Lincolnwood, IL 60646
(312) 679-1100

East and West

Brian R. Beihl
Associate Publisher
Robotics Age Inc.
174 Concord Street
Peterborough, NH 03458
603-924-7136

VBPA
Member of
Business Publications Audit

ROBOTICS ENGINEERING—(ISSN 0197-1905) is published monthly by Robotics Age Inc., Strand Building, 174 Concord Street, Peterborough, NH 03458, phone (603) 924-7136. Address subscriptions, changes of address, USPC Form 3579, and fulfillment questions to *Robotics Engineering* Subscriptions, 174 Concord Street, Peterborough, NH 03458. Second class postage paid at Peterborough, NH and at additional mailing offices. **POSTMASTER:** Send address changes to ROBOTICS ENGINEERING, 174 Concord St., Peterborough, NH 03458.

Subscriptions are $36 for one year (12 issues), $69 for two years (24 issues), $99 for three years (36 issues) in the USA and its possessions. In Canada and Mexico, subscriptions are $40 for one year, $77 for two years, $111 for three years. For other countries, subscriptions are $44 for one year, surface delivery. Air delivery to selected areas at additional charges, rates upon request. Single copy price is $3 in the U.S., $3.50 in Canada and Mexico, $4 in Europe, and $4.50 elsewhere. Foreign subscriptions and single copy sales should be remitted in United States funds drawn on a U.S. bank.

Address all editorial correspondence to the Editor at *Robotics Engineering*, Strand Building, 174 Concord Street, Peterborough, NH 03458. Opinions expressed by the authors of articles are not necessarily those of *Robotics Engineering*. Unacceptable manuscripts will be returned if accompanied by a self-addressed envelope with sufficient first class postage. Not responsible for lost manuscripts or photos.

16mm microfilm, 35mm microfilm, 105mm microfiche and article copies are available through University Microfilms International, 300 North Zeeb Rd., Ann Arbor, MI 48106.

Each separate contribution to this issue, and the issue as a collective work, is © 1986 Robotics Age Inc. All rights reserved. Copying done for other than personal or internal reference use without the permission of Robotics Age Inc. is prohibited. Requests for permission should be addressed in writing to *Robotics Engineering* Permissions, Strand Building, 174 Concord Street, Peterborough, NH 03458.

THE JOURNAL OF INTELLIGENT MACHINES

ROBOTICS ENGINEERING

JULY 1986 VOL. 8 NO. 7

EDITORIAL

2 Innovation and Judgement by Carl Helmers

FEATURES

5 Automated Painting System Installed On The Fly by Maurice Lande
Installing an automated spray painting line at an automotive plant presented one firm with particularly challenging problems—the existing manual line was not to be stopped during installation, and the urethane base and clear coats demanded special safeguards against sparking. This case history explains how these and other special requirements were satisfied.

8 Hazard Prevention in Automated Factories by James W. Collins
To ensure the safety of workers who must interact with robots and robotic systems, a threefold approach is outlined that addresses workstation design, employee training, and management initiative to provide a safe work environment.

12 The Fundamentals of Robot Kinematics by Nabih E. Bedewi
Off-line programming and trajectory planning often require that the engineer be familiar with the principles of robot kinematics. This overview defines robot positional kinematics through the use of simple geometry and expands the application to the more commonly used homogeneous transformations. Finally, a real-world example is provided.

21 Robots Prove Themselves in a Small Shop by Peter C. Doyle
One independent spray finishing shop's experience demonstrates that robots make economic sense in smaller volume operations.

24 Undesirable Environments: A Basis for Automation by Venkitaswamy Raju
The decision whether or not to automate must take into account a variety of factors, among them working conditions on the factory floor. Identifying undesirable conditions and assigning weight factors to them can help determine the suitability of automating a given process.

26 A Microcomputer Vision and Ranging System by Volker Petersen and John C. Even, Jr.
For applications where the cost of a full-scale machine vision system cannot be justified, an inexpensive system can be devised based on a 16-bit microprocessor. Although slower than special-purpose vision equipment, this approach nevertheless provides vision capabilities for a wide range of applications.

DEPARTMENTS

3 Letters
4 Calendar
4 Classified Advertising
27 Advertiser Index
29 In The Robotics Age
32 New Products

About the cover: This month's cover photograph was taken by Rick Lieder at the Industrial Technology Institute's Robotics Evaluation Center in Ann Arbor, Michigan. The facility performs cycling, point-to-point, path control, and continuous path tests for robot manufacturers and users to determine how a particular robot can be expected to perform and how it actually does perform. The end effector was designed specifically for the testing process. See the related arm kinematics article on page 12.

Editorial

Innovation and Judgement

BY CARL HELMERS

The imperative of all technologists is to master the present and improve the future of their respective technologies. The urge to improve is the itch that keeps us from settling into the status quo. The urge to "be practical" comes from that conservative desire to maintain the status quo. Yet somehow we humans, as engineers and enterprisers, manage to balance these contradictory urges. Overall, we keep improving our designs and systems as our engineering culture continues to evolve.

Experimentation has an attendant risk of less than optimal results, but without experimentation there is no progress. At the engineering level there is technological risk—will the new idea or process work? At the enterprise level there is entrepreneurial risk—will the technology or its products find a profitable market? At the human systems engineering level there is always management risk—will the systems and procedural framework for the technology be up to the requirements of the enterprise? Lately we've seen numerous examples of the risks of high technology enterprises—and the need for judgement along with innovation.

The practical use of innovative technology requires judgement. It also requires determination, patience, and resolve. A new method or technique is useless outside of the context in which it will be used. A recent *Wall Street Journal* article on the trials and tribulations of U.S. automotive uses of robotics makes the point that simply slinging resources at the latest technology will not necessarily produce instant results. (See "Tricky Technology: Auto Makers Discover 'Factory of the Future' Is Headache Just Now," by Amal Nag, *WSJ*, May 13, 1986, page 1.) With relatively higher profits due to the protectionist walls of quotas in recent years, the U.S. automotive companies, according to the article, have been spending freely in order to highly automate vehicle production. Not all has gone smoothly. The article makes the point also that much of this country's manufacturing turns to the automotive companies' processes for inspiration, and their experiences might very well have some impact on the overall pace of automation activities throughout the land.

What the automotive manufacturers are really discovering, however, is the need for judgement—evaluation of an innovation in the full context of an enterprise and its R&D operations. To create the putative factory of the future we need to understand what the goal is and how to best achieve that goal, and to make a definite commitment to achieve it, backed up by resources. All of this requires evaluation and judgement calls.

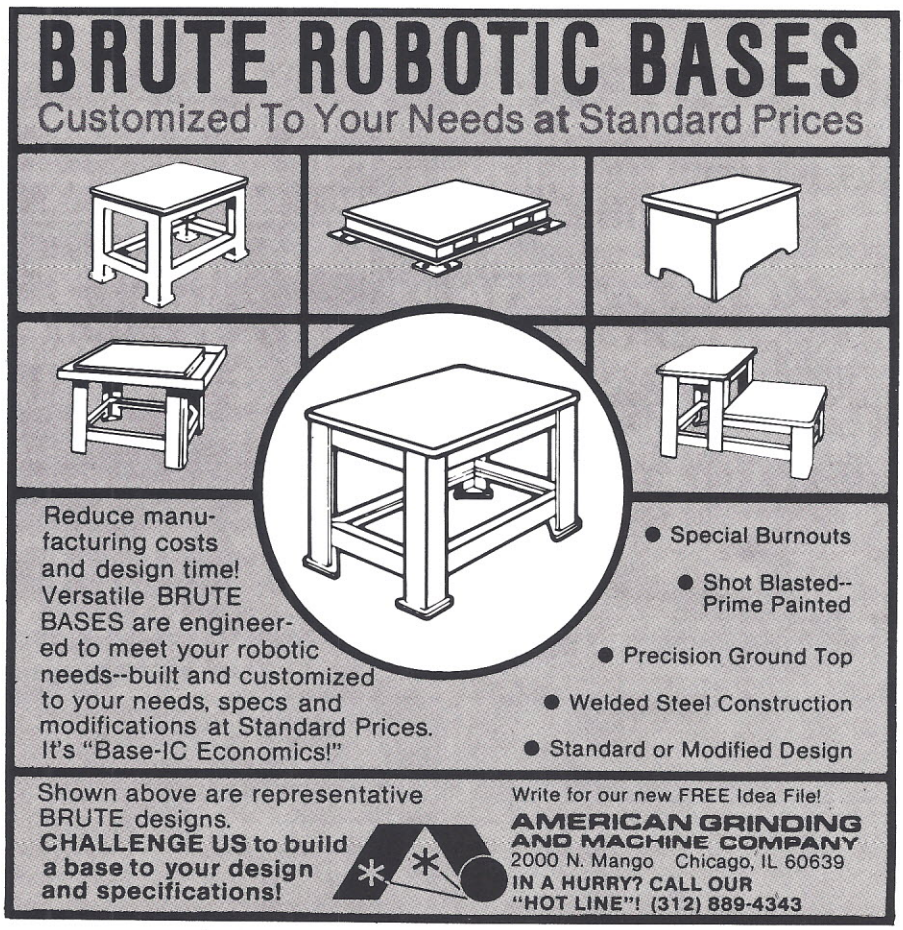
The easy part has already been done by the auto companies—they've made their commitment and backed it up with resources. Now comes the hard part: engineering the automation to achieve their manufacturing goals. Apparently, a judgement call has been made to the effect that full automation of a U.S. automobile factory from scratch by means of a fresh innovative design is the right way to go. Thus we see the new factories being built—with long debugging periods as the myriad details are coordinated. This is one way to achieve progress along the learning curve of a new technology.

But starting from scratch is not the only way to achieve automation. People sometimes deride the concept of "islands of automation" as a piecemeal approach to improved productivity. But consider the idea of such islands, coupled with the idea of communication among them to coordinate the movement of materials and data. Perhaps, if anything can be called a major technological benefit to be shared by all industries but coming from the G.M./Ford/Chrysler automation push, it is the idea of communication. Out of G.M., a major user of computers in its manufacturing processes, comes a major industrial digital communications protocol.

Now let's get back to our island theme. The conservative side of our engineering nature is always present. Islands of automation aggregating into larger and larger subsections of a manufacturing process is a conservative and slower strategy, but it requires just as much commitment and attention to the ultimate goal.

In the computer and electronics field, where modularity and top-down division of functions is the norm, some of the more advanced incremental approaches to automation already exist. Thus we see semiconductor manufacturers steadily increasing automation of their die-making and assembly lines, even to the point where in some cases it is getting less expensive to manufacture semiconductors stateside. In a related area, we see how the rigid disk manufacturers are automating materials handling incrementally, starting at the center with the coating lines in clean rooms and growing at both ends: backward toward incoming materials preparation and forward through final polishing, inspection, and assembly.

The gradual introduction of a new technology within a long-term strategy of reaching the goal of radical improvements has been a characteristic of the entire history of our civilization. Each incremental improvement is judged within the context of its application. On balance, all the improvements add up. Then, a decade or so later, we look back and say, "How could we ever have done without X?" The principle here is to manage the risk of innovation by making each judgement call a relatively small risk in the context of a long-term strategy of innovation. The long-term goal means that the innovation will proceed apace; in the short term, the idea is to manage risk so that there will *be* a long term for the enterprise or organization involved. Innovation requires judgement. ■



Circle 31

Letters

I am writing regarding the book review written by Robert E. Parkin, Ph.D., and published on page 37 of your April 1986 (Vol. 8, No. 4) issue. This review contains factual errors and does not give your readers an accurate picture of the book Introduction to Robotics, Mechanics and Control *by John J. Craig (Addison-Wesley). I am very familiar with Craig's book and have taught a first-year graduate course using his manuscript for two years. It has been my experience that this book is very easy to teach from. Moreover, it has received rave reviews from my students.*

Your reviewer errs badly when he criticizes Craig's statement that "only in special cases may robots with six degrees of freedom be solved analytically." Craig is absolutely correct and your reviewer is absolutely wrong. Six degree of freedom systems cannot in general be solved in terms of closed form solutions. Your reviewer is also in error when he implies that prismatic joints are not defined and that Craig in the main plunks underived formulas on the reviewer's lap. In fact, Craig presents a very detailed development of the basic equations for the kinematic, static, and dynamic analysis of manipulators.

Unfortunately, your reviewer does not comment on Craig's treatment of Pieper's solution and his development of the computed torque control method including operational space control. These topics are not found in any other texts presently available.

In my opinion, your reviewer has done your readers a disservice in not strongly commending this outstanding book to their attention.

Bernard Roth
Professor
Mechanical Engineering Department
Stanford University
Stanford, CA 94305

Dr. Parkin responds:

Professor Roth says, "Your reviewer errs badly when he criticizes Craig's statement that 'only in special cases may robots with six degrees of freedom be solved analytically.' Craig is absolutely correct and your reviewer is absolutely wrong." Craig states, "A manipulator is considered solvable if the joint variables can be determined by an algorithm which allows one to determine *all* the sets of joint variables associated with a given position and orientation," and cites B. Roth, "Performance of Manipulators from a Kinematic Viewpoint," Performance Evaluation of Manipulators, National Bureau of Standards, special publication, 1975. A forward kinematic solution uses the base orientation and position and the joint status to determine the position space (which is usually end effector position and is often also the end effector orientation—such a robot then being defined as orientable). The position space will be unique and can always be found. The inverse kinematic solution uses the base orientation and position and the position status to determine the joint space. Provided the robot is capable of satisfying the position status, and it usually is, the joint space can always be found. Thus, I am correct and both Craig and Roth are incorrect since, as stated in my review, all robots are solvable.

Roth links "Six degrees of freedom systems cannot in general be solved in terms of closed form solutions" to two prior sentences in an ambiguous and misleading way. More than one general class of such robots have closed form solutions. A six degree of freedom orientable robot has no more than two possible inverse kinematic solutions, and so, according to Craig's definitions, all such robots have a closed form inverse kinematic solution, and Roth apparently interprets analytic to mean closed form. I did not apply the same interpretation.

In my review I stated, "The initial specification of robot joints is imprecise, incomplete, and misleading." I believe this statement to be true. Is the prismatic joint a sliding joint as possibly implied on page 5, and where is the mathematical specification of any of the common robotic joints? The family of rotation matrices is so important to robot kinematics that these derivations should be explicitly presented. Roth claims that, "Craig presents a very detailed development of the basic equations for the kinematic . . . analysis of manipulators," but why not address my specific example? Where is the justification for "we stack these three unit vectors together as the columns of a . . . rotation matrix"?

Roth may be correct in chiding me for the omission in the review of Craig's treatment of Pieper's fine work. I plead space considerations and an emotional bonding to a technique for which such material is inapplicable. It must be gratifying to hear students rave about a book, and [I] congratulate Craig, but I would have done the readers of *Robotics Engineering* a disservice by presenting a review that was "not . . . an accurate picture of the book."

Dr. Robert E. Parkin
Department of Electrical Engineering
One University Avenue
University of Lowell
Lowell, MA 01854

Robotics Engineering welcomes letters of general interest to our readers. Opinions, questions, and concerns in the area of industrial robotics should be addressed to:

Lorraine Cleveland
Editorial Coordinator
Robotics Engineering,
174 Concord St.
Peterborough, NH 03458.

Calendar

JULY

14–18. Computer Vision and Image Processing. Chrysler Center for Continuing Engineering Education, University of Michigan, Ann Arbor, MI. Contact: Engineering Summer Conferences, 200 Chrysler Center—North Campus, The University of Michigan, Ann Arbor, MI 48109, telephone (313) 764-8490.

AUGUST

5–7. 1986 Western Plant Engineering Conference and Western Plant Engineering, Material Handling & Packaging Show. Long Beach Convention Center, Long Beach, CA. Contact: William H. Slater, Vice President-Director, Western Plant Engineering Conference, 13752 Hewes Ave., Santa Ana, CA 13752, telephone (714) 544-4184.

11–13. Third International Robotic Systems Education and Training Conference. Plymouth Hilton Inn, Plymouth, MI. Contact: Mary Dombrowski, SME Special Programs Division, Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500, ext. 392.

13–15. Machine Vision for Educators: A Hands-on Clinic. Plymouth Hilton Inn, Plymouth, MI. Contact: Mary Dombrowski, SME Special Programs Division, Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500, ext. 392.

17–20. International Conferences on Planning and Design Methodology I. Boston Park Plaza Hotel and Towers, Boston, MA. Contact: Prof. Gerald Nadler, University of Southern California, University Park, Los Angeles, CA 90089-1452, telephone (213) 743-2705.

18–22. 13th Annual Conference on Computer Graphics and Interactive Techniques. Dallas Convention Center, Dallas, TX. Contact: SIGGRAPH '86, Conference Management, 111 East Wacker Dr., #600, Chicago, IL 60601, telephone (312) 644-6610.

20–22. Applying Machine Vision to Your Manufacturing Process: A Hands-on Workshop. Cambridge, MA. Contact: Joanne Rogers, Special Programs Division, Society of Manufacturing Engineers, One SME Dr., Dearborn, MI 48121, telephone (313) 271-0039. (To be repeated **25–27 August** in Cambridge, MA, **10–12 September** and **15–17 September** in Minneapolis, MN.)

26–29. Singapore International Technology Exhibition and Conference. Singapore World Trade Centre, Singapore. Contact: Carol Skinner, Cahners Exposition Group, 7315 Wisconsin Ave., PO Box 70007, Washington, DC 20088, telephone (301) 657-3090.

SEPTEMBER

9–11. Hazardous Materials Management Conference and Exposition. Metro Toronto Convention Center, Toronto, Ontario, Canada. Contact: Bob Myhelic, Tower Conference Management Co., 331 W. Wesley St., Wheaton, IL 60187, telephone (312) 668-8100.

9–11. Midcon/86 High Technology Electronics Exhibition and Convention. Dallas Convention Center, Dallas, TX. Contact: Electronic Conventions Management, 8110 Airport Blvd., Los Angeles, CA 90045, telephone (213) 772-2965.

10–11. Mid-Atlantic Design and Production Exhibition and Conference '86. Valley Forge Convention and Exhibit Center, Valley Forge, PA. Contact: Mid-Atlantic Electronics '86, International Marketing Services Ltd., 1030 South LaGrange Rd., LaGrange, IL 60525, telephone (312) 354-3900.

11–12. Surface Mount Technology. Boston, MA. Contact: Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500.

22–25. Vision West at Ultratech. Long Beach Convention Center, Long Beach, CA. Contact: Gregg Balko, Technical Activities Department, Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500, ext. 368.

23–25. Artificial Intelligence and Advanced Computer Technology Conference/Exhibition. Rhein-Main Halle, Wiesbaden, West Germany. Contact: Tower Conference Management Co., 331 W. Wesley St., Wheaton, IL 60187, telephone (312) 668-8100.

29–October 2. 16th International Symposium on Industrial Robots. Brussels Exhibition Centre, Brussels, Belgium. Contact: ISIR-Robotex, Brussels International Trade Fair, Place de Belgique-Belgieplein, B-1020, Brussels, Belgium, telephone (32-2) 478 48 60.

OCTOBER

13–15. Stepping Motor Workshop. Howard Johnson Motor Inn, Portsmouth, NH. Contact: Mrs. Lee Wilhelm, University of New Hampshire, The Consulting Center, Horton Social Science Center, Durham, NH 03824, telephone (603) 862-3750.

16–17. Brushless Motor Workshop. Howard Johnson Motor Inn, Porstmouth, NH. Contact: Mrs. Lee Wilhelm, University of New Hampshire, The Consulting Center, Horton Social Science Center, Durham, NH 03824, telephone (603) 862-3750.

26–31. Cambridge Symposium on Optics and Optoelectronics/Advances in Intelligent Robotics Systems. Cambridge, MA. Contact: SPIE, PO Box 10, Bellingham, WA 98227-0010, telephone (206) 676-3290.

27–29. Interface International in Europe. Parc des Expositions, Porte de Versailles, Paris, France. Contact: Linda Hanson, The Interface Group, Inc., 300 First Ave., Needham, MA 02194, telephone (617) 449-6600.

Classified Advertising

FOR SALE - Two IBM Robots Model 7535 complete with stand. Programmable in a high level (AML) language. Programmable XY Theta position repeatable to .002". Maximum payload 13.2 lbs. Call or write: de Haart, Inc., 12 Wilmington Road, Burlington, MA 01803 (617) 272-0794.

Automated Painting System Installed On The Fly

Maurice Lande
AKR Robotics, Inc.
35367 Schoolcraft
Livonia, MI 48150

The world of robotics is not all flash and glamour. After the lights have dimmed at the robot show, the harsh realities of implementing units into systems on the plant floor reappear, framing the day-to-day challenges that face those within the industry.

Recently, AKR Robotics, Inc., of Livonia, Michigan was presented with an extreme installation challenge. An automobile manufacturer specified that AKR implement an automated system for electrostatic painting of front and rear fascia assemblies at one of its assembly plants. The hitch came in the form of a production schedule—the manual line was producing 76 front and rear fasciae per hour on a two-shift schedule, with a third shift required for cleanup and maintenance. Under no circumstances could the installation, programming, and debugging of the automated system interfere with that production.

Further, the automotive customer insisted that the new system fit into the space previously occupied by the manual system, and that the installation procedures not interfere with plant-level work rule agreements.

In other words, AKR was asked to unobtrusively introduce an automated painting cell, complete with robots, into a manual operation without disrupting production in any way.

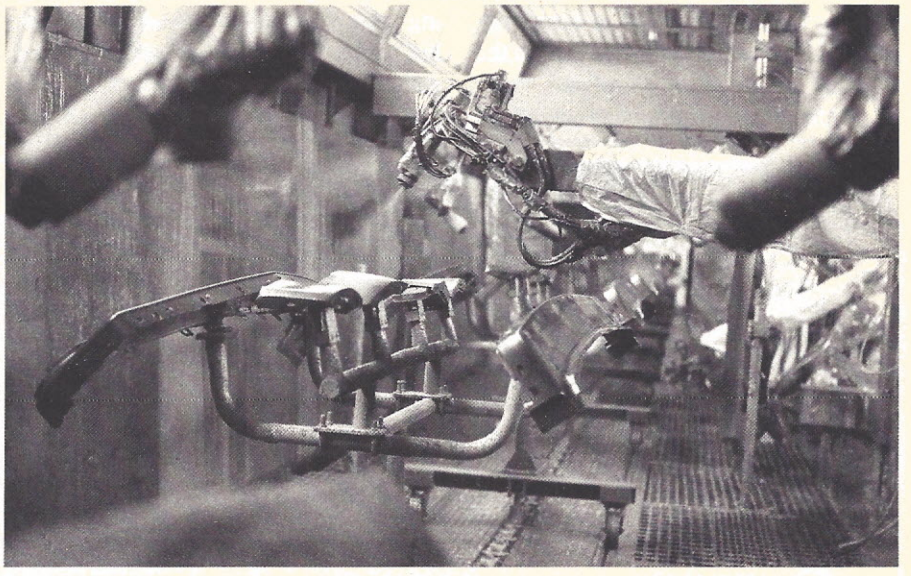


Photo 1. The paint line consists of four stations, each including six fixed automatic spray guns (such as those in the upper left foreground) and one robot.

As per the request of the customer's process engineers, the design concept of the system was based on the simultaneous use of two methods of coating application in the same cell. The line itself would consist of four stations, to include six automatic but fixed spray guns and one robot (Photo 1). The first two stations would apply a base coat and the second two stations would apply the clear coat.

Paramount among the customer's concerns was that the fasciae be of high quality, both in terms of coverage and aspect. In order to ensure the coating quality, AKR provided three-way analog control to each spray gun. Paint flow, air flow, and fan width were constantly monitored and compensated.

The AKR 3000 robot is a six-axis, electrohydraulic manipulator capable of end-of-arm loads to 33 lb. providing 33.6 ft-lb. of wrist torque. Speeds are above 6.6 ft/sec., and static repeatable accuracy is within 0.15 in. The AKR 3000 encom-

passes a work envelope of more than 100 ft³, which can be extended when payloads permit (Photo 2).

Programming is via direct lead-through of the arm, by means of the unique off-arm light-weight Syntaxor, or through off-line programming using AKR's Advanced Analytical Programming terminal and software. A unique safety feature is a photo-electric anticollision system on the horizontal arm that brakes the robot almost instantaneously upon interference with the light beam.

All spray guns—both those in fixed operations and those mounted on the robots—were supplied by a sister firm, Kremlin. These guns were specially designed for robotic applications and thus have no internal adjustments. All parameter settings are remote and controlled by transducers, allowing precise and flexible selections of fluid flow, atomizing, and fan width of each style, color, and section of the part being painted.

Since the electrostatic effect is variable, the guns had to be capable of being triggered off and on. Furthermore, as both the base and clear coats are urethane, making hydrocarbon safety considerations

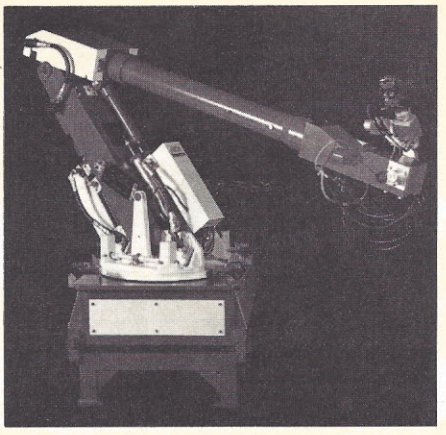


Photo 2. The AKR 3000 is a six-axis electrohydraulic manipulator. During spraying operations it is protected by a plastic shroud.

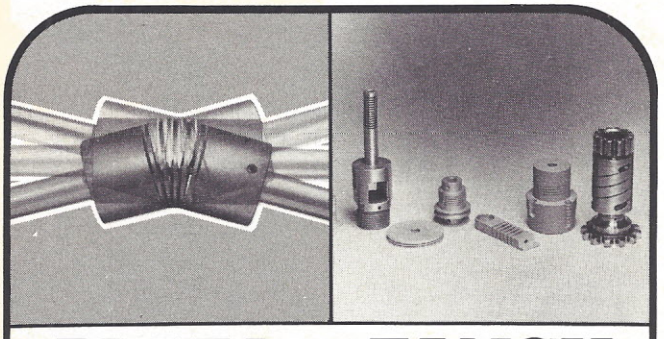
critical and sparking unacceptable, each gun incorporates an internal generator with power delivered by a low-voltage cable.

Another constraint was the need to change color on the fly. Because of its ability to move away from the part, changing color is relatively easy with the robot, but much more difficult with the fixed guns. The guns were mounted close to the part, greatly restricting the space and time in which gun nozzles could be blown free of the old paint without misapplying paint to a part. AKR's solution was a combination of special dump-outs combined with a high-pressure flush, well in excess of normal painting pressures.

Beyond considering the necessity of intricate timing of paint application to parts as they come down the conveyor—especially in light of the fixed guns— AKR was required to maintain painting quality in the event of conveyor shutdown, a common occurrence. The challenge was to prevent overspray in the startup and shutdown mode, requiring extremely close monitoring of conveyor speeds, including minute acceleration and deceleration variables that could result in a poorly coated part.

To that end, AKR supplied a control that monitors both the conveyor control and the actual conveyor speed, compares variances, and compensates the guns accordingly in both startup and shutdown modes.

Another consideration was the electrostatic coating being used on non-conductive parts. AKR solved that problem by supplying metallic part carriers that



PLAIN or *FANCY*

OFF THE SHELF or tailor-made, **Heli-Cal® one piece flexible couplings are more** than a means to connect two shafts.

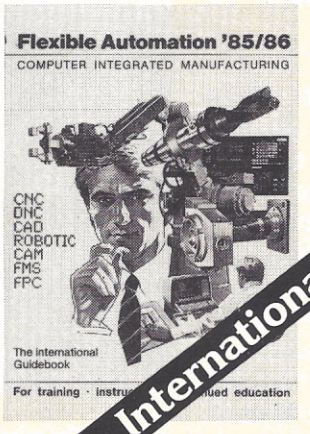
They do an ordinary job or fill a special need. They may be springs. U-joints. Misalignment correctors. Torque transmitters. Or standard Heli-Cal flexures with custom end connections.

The choice is yours as to specs for flexibility, rigidity, materials and sizes. Application possibilities are virtually anything you want them to be.

A specification catalog is your first step to this plain (or fancy) connection. When you see it, you'll be assured of the superb engineering and unique capabilities we offer. Request yours today.

HELICAL
PRODUCTS COMPANY, INC.
901 West McCoy Lane
P.O. Box 1069
Santa Maria, CA 93456
805/928-3851 TWX: 910/351-5856

Circle 39



1 copy $ 13.50
2–5 copies
$ 13.00

The International Bestseller

6–20 copies
$ 12.00
+ shipping and handling

The International Guidebook and Reference book of Computer Automated Manufacturing. A superior book for training, instruction and continued education in the field of CNC–DNC–CAD–CAM–FMS–FPC–Robotics.

Please order now:

BECKER PUBLISHING COMPANY, INC.
P.O. BOX 8396, NAPLES, FL 33941, USA
PHONE: (813) 947-4800

Circle 34

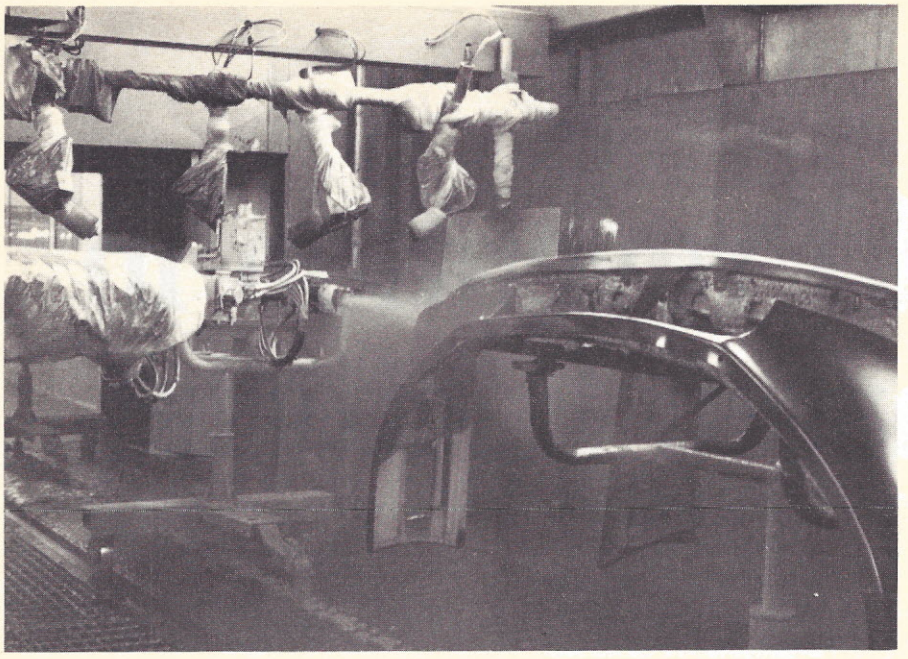


Photo 3. The first two paint stations apply a base coat to the fasciae and the second two lay on a clear coat. Both coatings are urethane, so the possibility of sparking had to be eliminated.

provided an effective electrical ground (Photo 3).

Programming the robots was accomplished via AKR's lightweight Syntaxor. The best operator manipulated the robot manually to paint the parts at half speed, and the painting programs were automatically speeded up to match actual conveyor demands.

Because of the environmental constraints, AKR required four months to install, debug, and program the line—longer than the normal time for such operations. But the payback has been operating the system for six months with two shifts up and a third down for maintenance every day without losing a single part from robot downtime.

Just as important, whereas previously eight people were needed per shift to accomplish the job, now only one person is assigned to the automatic cell, and that individual's responsibilities are mostly devoted to monitoring quality to ensure against problems that might arise from inconsistencies in coating materials.

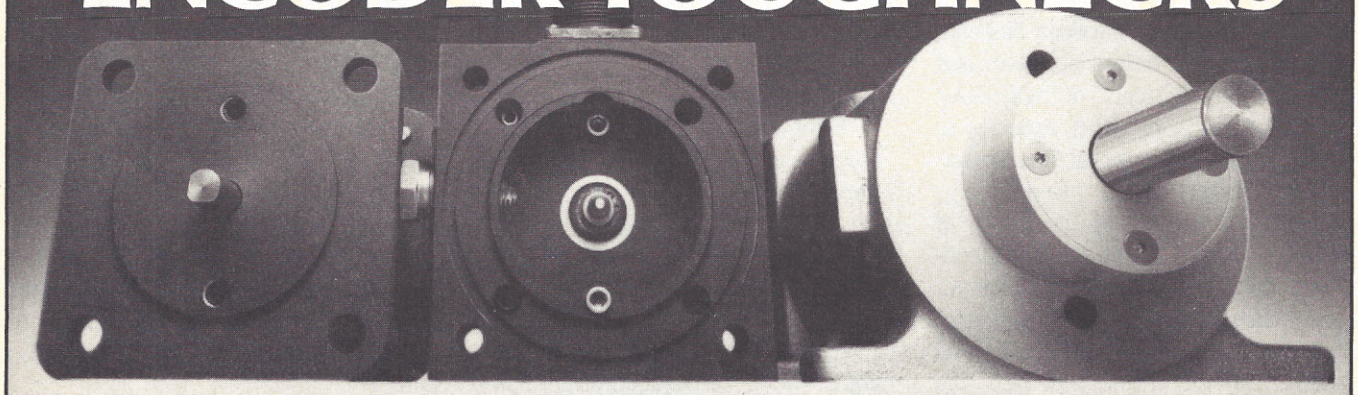
Maurice Lande is President of AKR Robotics, Inc.

Reader Feedback

To rate this article, circle the appropriate number on the Reader Service card.

1	11	21
Excellent	Good	Fair

ENCODER TOUGHNECKS



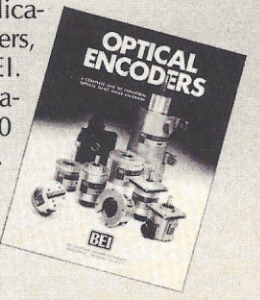
It's a fact. When your applications get tough, the last thing you want on your team is a lightweight.

Enter The Toughnecks from BEI. Three ruggedly protected encoders ready for action in well-logging, railroading, robotics or in *any* hostile environment.

There's the H-37, housed in a sturdy, low-profile aluminum casing—perfect where space is at a premium; the H-38, with a hard anodized finish and a UL listing—when an explosion-proof encoder is a must; and our ultra-heavy-duty encoder, the H-40, with foam mounting to protect the internal encoder from shocks of up to 200 Gs.

So before your heavy-duty applications rough up your existing encoders, call in The Toughnecks from BEI.

For our new, 20-page Specification Guide, call or write BEI at 7230 Hollister Ave., Goleta, CA 93117. 805/968-0782 Telex 888069 BEI IED.



BEI Motion Systems Company
Industrial Encoder Division

Circle 33

Hazard Prevention in Automated Factories

James W. Collins
National Institute for
Occupational Safety and Health
944 Chestnut Ridge Road
Morgantown, WV 26505-2888

Some estimates place the current United States industrial robot population at 17,000, with total projected installations estimated at 100,000 by 1990. Yet, like many new technologies, the industrial robot was introduced into the workplace without consideration to certain safety and health impacts. Today, only limited guidelines are available to assist informed engineering judgment in the safe installation and use of these robots.

The two primary guidelines are the voluntary "Proposed American National Safety Standard for Industrial Robots and Industrial Robot Systems" of the Robotic Industries Association (RIA), expected to receive official ANSI approval this summer, and the NIOSH Alert, "Request for Assistance in Preventing the Injury of Workers by Robots." Unless safety is considered during the design, installation, maintenance, and operation of industrial robot systems, serious and even fatal hazards can be introduced into the workplace.

To date, one robot-related fatality has occurred in the United States. The July 21, 1984 accident took place when the operator of an automated die-cast system was pinned between the rear of the robot arm and a steel safety pole (1). (On January 25, 1979 a worker was struck and killed by an automated guided vehicle, but since the device did not qualify as a robot by RIA's definition of the term, the accident was not reported as robot-related.) In Japan, where more robots are used, five robot-related fatalities had occurred by the end of 1984 (2).

A comparative analysis of these fatalities reveals several significant similarities. First, all the victims were experienced and trained in robotic operations and safety. Second, all had entered the working range of a robot under power by either climbing over perimeter guarding or overriding existing safeguarding devices. Finally, all the victims were struck from behind and pinned between the robot and stationary fixtures or equipment.

NIOSH RECOMMENDATIONS

Steps for preventing robot-related traumatic injuries and fatalities can be taken by following a threefold approach that addresses the design of robotic workstations, training of employees, and a conscientious effort on the part of management to provide safe working conditions. The recommendations are based on a field evaluation by NIOSH of the first robot-related fatality in the United States and the RIA's proposed standard. This standard is voluntary and neither the RIA nor NIOSH makes a determination whether any robot manufacturer or user is or is not in compliance with this standard.

Workstation Design. After the initial capital investment in an industrial robot, careful consideration should be given to safely integrating the robot with its associated equipment. During the design of the robotic workstation, attention should be given to providing adequate clearances between the robot and related equipment to minimize pinch points within the work envelope. Additional caution should be exercised when industrial robots are installed in existing workstations originally designed to accommodate only a human worker. Because industrial robots usually require more space than humans, equipment or machinery interfaced with the robot may need to be moved back or rearranged to eliminate pinch points. Fixed poles should not be used to restrict robot arm movement. While they are intended to limit hazardous, uncontrolled movements of the robot, these poles can introduce person-sized pinch points that can be fatal, as was illustrated by the fatality investigated by NIOSH. The victim's coworkers who were interviewed were unaware of the pinch point created by the pole.

When perimeter guarding is selected, several options are available that provide varying degrees of protection. Safety rails, chains, or ropes with openings through which personnel can walk serve only as awareness barriers and are inadequate for preventing unauthorized entry of workers or containing flying workpieces. If the goal is to prevent unauthorized entry and contain flying workpieces, a safety fence at least six feet high with an interlocking gate should be provided. The fence should completely enclose the robot's work

About NIOSH

NIOSH, the National Institute for Occupational Safety and Health, is the federal agency responsible for conducting research aimed at the development of effective intervention methods for dealing with occupational safety and health problems. NIOSH's Division of Safety Research (DSR) is the institute's arm for accident and injury prevention programs. The mission of DSR is to decrease the number and severity of workplace-related injuries by designing, developing, and conducting research projects that yield results with real-world impact.

DSR's research strategy for industrial robots is aimed at identifying hazards and recommending solutions before accidents occur. As part of this initiative, several research studies addressing the safety of automated technology are being conducted. The research includes an examination of several types of electronic sensors to determine their effectiveness for accurately detecting human presence in robot work zones. Sensor technologies to be evaluated include capacitive devices, pressure sensitive mats, ultrasonic sensors, and light curtains.

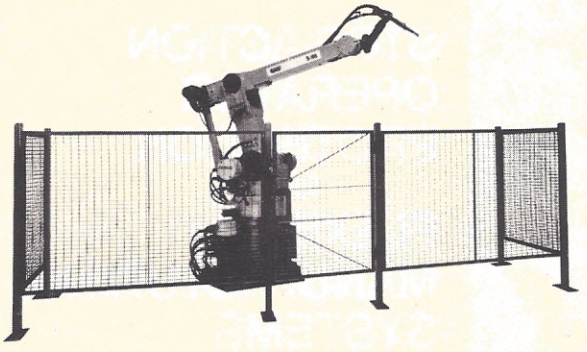
Another project is to develop safety guidelines for the industrial robot maintenance technician, a job category identified as one of the higher risk classifications associated with industrial robots. An experimental study of what velocity can be considered a "safe" slow speed for robot programming and maintenance purposes is also under way. The RIA's standard proposes that a slow speed of 10 in./sec. be used during maintenance and programming tasks. Ten in./sec. is strictly an estimate; no experimental determination has thus far been made of a speed that takes into account a human's ability to recognize and react to a perceived hazard.

envelope. In spray painting or other applications where toxic gases could be emitted, a nonporous enclosure can provide a safeguard as well as contain the contaminants.

In reference to the interlocking feature associated with perimeter guarding, RIA's proposed standard states that "an interlocked barrier guard shall prevent access to the restricted work envelope except by opening an interlocked gate. Opening of the interlocked gate shall either stop the robot and remove drive power to the robot's actuators or stop automatic operation of the robot and any other associated equipment that may cause a hazard. Returning the system to automatic operation shall require both closing the interlocked gate and deliberately activating the controls used to restart automatic operation." Care should therefore be taken to install interlock devices that cannot be bypassed easily.

Another approach to perimeter guarding is a photoelectric presence-sensing device, sometimes called a light curtain. When someone enters the work envelope and interrupts the photoelectric sensing plane, the light curtain halts machine motion. In

ROBOT GUARDS



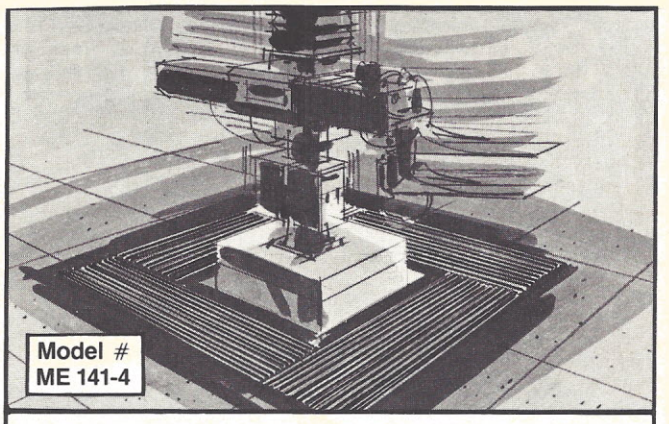
Woven Wire Panels bolt to steel posts. Guard defines work envelope and protects employees. Parts in stock for quick delivery.

WIRE CRAFTERS INC.

6208 STRAWBERRY LANE
LOUISVILLE, KY 40214 • 1-502-363-6691

1-800-626-1816

Circle 47



GuardianMat Safety Switch

protects lives & equipment

MillerEdge

- Failsafe construction for total reliability
- 100% flexible to withstand impact & resist damage
- Custom sizes & shapes to your exact specs
- Heavy duty non-skid surface resists common greases & oils

Call MillerEdge for free sample.

Concord Industrial Park, P.O. Box 38, Concordville, PA 19331
(215) 459-4241

Circle 42

addition to perimeter guarding, visible markings outlining the full range of robot motion should be indicated on the floor. Painted markings, tape, or other highly visible material should be used to identify the maximum extension of the robot's arm.

Control panels from which automatic operation can be initiated should never be located within the work envelope. The control panel and diagnostic instrumentation should be installed outside the robot's work envelope to allow for safe startup, stopping, and troubleshooting. The RIA's proposed standard states also that every robot control station and teach pendant should have an emergency stop function using hardware-based components. The emergency stop function should override all moving parts to stop. The pushbuttons that initiate emergency stops should be red, either palm or mushroom type, and that initiate emergency stops should be red, either palm or mushroom type, and unguarded and unobstructed. They should be installed near areas of frequent exposure to hazards, and personnel should be familiar with their location and function. The teach pendant, which is a handheld control unit used to program or move the robot, should also include an emergency stop button.

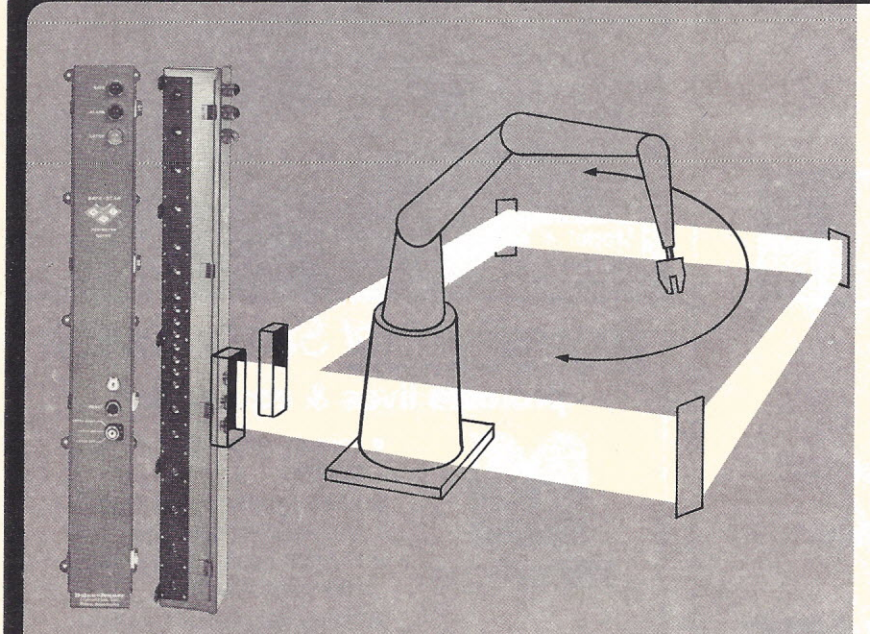
Training. Training should be provided for all personnel who will be programming, operating, or performing maintenance on industrial robot systems. For training to be effective, it must be specific to the worker's job and to the particular robot application. Personnel required to interact with the robot should be familiar with the safeguarding system and the placement and function of all emergency stop buttons. Training should emphasize the hazards associated with entering the robot's work envelope and familiarize personnel with safe stopping and restarting procedures. Programmers should not create unnecessary pinch points while teaching the robot to perform specific tasks. Periodic refresher courses should be provided to keep workers aware of hazards and the precautions for avoiding injury.

For training to be effective, it must be specific to the worker's job and to the particular robot application. Periodic refresher courses should be provided to keep workers aware of hazards and the precautions for avoiding injury.

Management. When purchasing an industrial robot, buyers should take advantage of available sources for comprehensive advice on designing safeguarding systems. Information can be obtained from robot manufacturers, automated systems specialists, the RIA, and government agencies such as NIOSH or the Occupational Safety and Health Administration.

A systematic safety analysis of the proposed robot application and workstation will help ensure that no hazards are overlooked. Management should ascertain that the company has a written robotics safety policy that has been explained to all personnel who will be working with the robot. Additionally, this policy should state who is authorized to interact with the

SAFESCAN® PERIMETER GUARD



STOP-ACTION OPERATOR PROTECTION for FLEXIBLE MANUFACTURING SYSTEMS

- Programmable infrared invisible light safety screen
- Protects 35″ and 70″ heights
- All models have 65′ range
- Easy installation—relocateable
- NEMA 12 enclosures

LOW COST 1 to 4 side protection—*"We do it with mirrors"*

SEND FOR BULLETIN 977

Dolan-Jenner Industries, Inc. A Unit of Barry Wright Corp.

Box 1020, Blueberry Hill Industrial Park, Woburn, Ma 01801
Tel. 617-935-7444 Telex 94-8161

Dolan-Jenner, Inc . . . the only company to design, engineer and manufacture both fiber optics and electronic controls in a single facility.

Circle 38

robot. Supervisors should strictly enforce the rules in the safety policy and keep in mind that newly trained employees may require close supervision until they are thoroughly familiar with the robotic system. Supervisors should also be aware that robotics personnel who are experienced with automated machinery may become bored, overconfident, or unconcerned for their own safety, attitudes that increase the possibility of risk or injury.

A qualified person should be posted at the control panel during brief corrective or preventive maintenance activity. This person should be given the specific responsibility of protecting against unauthorized actuation of the controls that initiate automatic operation. When maintenance of longer duration is being performed, "lockout" and "tagout" procedures should be implemented to ensure that the robot or associated equipment is not reenergized before the activity has been completed. The points of control should be secured (locked out) such that reenergizing the robotic system requires the use of special equipment or tools available only to the person who applied the lockout. A warning (tagout) should be posted at the point(s) of control that provides information as to why the energy sources have been isolated, the date, the person(s) responsible for the tagout, and the person(s) responsible for the work to be accomplished. In addition, access to the control point(s) must be limited to persons who are trained to understand and observe the posted warning.

SUMMARY

No single solution guarantees the safety of workers who will be interacting with industrial robots and robotic systems. To provide safe working conditions a threefold approach is in order, one that addresses the careful design of the robotic workstation, the thorough training of all employees whose work will involve them with industrial robots, and management initiative to provide a safeguarding system and safe work practices that will prevent robots from injuring workers.

REFERENCES

1. National Institute for Occupational Safety and Health. "Request for Assistance in Preventing the Injury of Workers by Robots." *NIOSH Alert*, (December 1984).
2. Parsons, H. McIlvaine. "Human Factors in Industrial Robot Safety." *Journal of Occupational Accidents*, 8, Amsterdam, The Netherlands: Elsevier Science Publications B.V. (1986).

FOR FURTHER READING

National Institute for Occupational Safety and Health. "Guidelines for Controlling Hazardous Energy During Maintenance and Servicing." *NIOSH Publication No. 83-125* (September 1983), 12–13.

Robotic Industries Association. "Proposed American National Standard for Industrial Robots and Industrial Robot Systems." (July 1985).

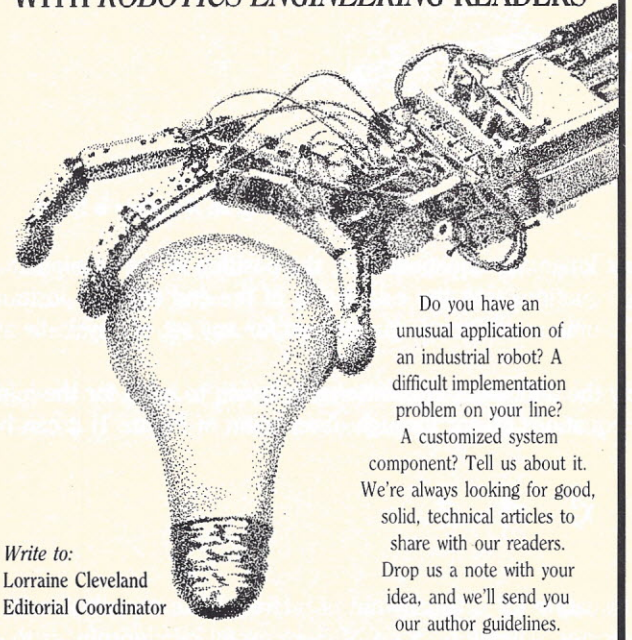
James W. Collins is a Mechanical Engineer in the Division of Safety Research of the National Institute for Occupational Safety and Health.

Reader Feedback

To rate this article, circle the appropriate number on the Reader Service card.

2	12	22
Excellent	Good	Fair

SHARE YOUR IDEAS
WITH *ROBOTICS ENGINEERING* READERS

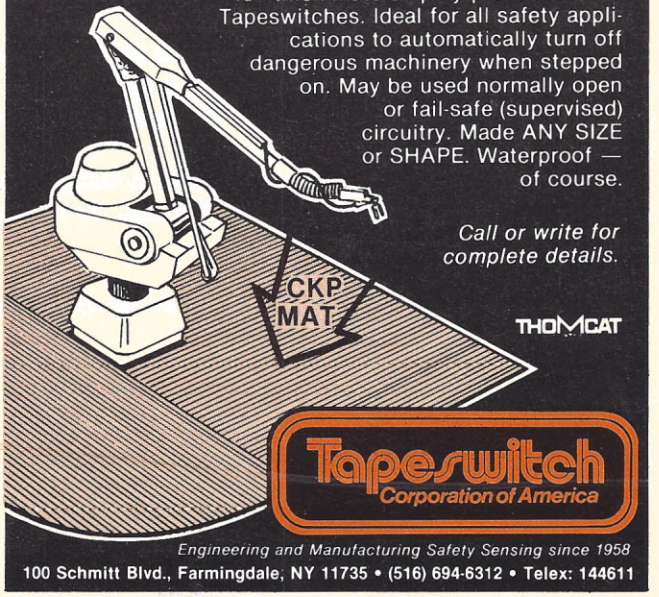


Do you have an unusual application of an industrial robot? A difficult implementation problem on your line? A customized system component? Tell us about it. We're always looking for good, solid, technical articles to share with our readers. Drop us a note with your idea, and we'll send you our author guidelines.

Write to:
Lorraine Cleveland
Editorial Coordinator

THE JOURNAL OF INTELLIGENT MACHINES
ROBOTICS ENGINEERING
174 Concord Street,
Peterborough, NH 03458

ROBOT SAFETY
CKP SWITCH CARPETS Put Robots On Hold — Prevent Accidents!



Our rugged press-at-any-point ½" thick mats employ proven reliable Tapeswitches. Ideal for all safety applications to automatically turn off dangerous machinery when stepped on. May be used normally open or fail-safe (supervised) circuitry. Made ANY SIZE or SHAPE. Waterproof — of course.

Call or write for complete details.

THOMCAT

Tapeswitch
Corporation of America

Engineering and Manufacturing Safety Sensing since 1958
100 Schmitt Blvd., Farmingdale, NY 11735 • (516) 694-6312 • Telex: 144611

Circle 45

The Fundamentals of Robot Kinematics

Nabih E. Bedewi
Applied Engineering Research, Inc.
PO Box 21, Baltimore Boulevard
Hyattsville, MD 20781

Over the past decade, the field of robotics has evolved from being an art of design to a sophisticated science of precision engineering and advanced controls. The demands of the manufacturing industry for faster, more repeatable, more accurate machines with improved resolution led to the implementation of more complex control techniques that had previously been strictly theoretical and mathematical in nature.

The use of such techniques in either the design of a robot control system or in off-line programming and trajectory planning has placed great demands on engineers and operators. Particularly, they have had to become familiar with robot kinematics and dynamics. For many practicing engineers, robot kinematics and computational linear algebra did not constitute a formal part of their education. The consequence, of course, is that occasionally they are subjected to the nightmare of having to read a technical publication on the subject.

The objective of this overview article is to define robot positional kinematics through the use of simple geometry, and then to expand the application to the more commonly used homogeneous transformations. A systematic explanation of the construction of transformation matrices will be presented, followed by an example demonstrating how they can be obtained on a real industrial robot to describe the position and orientation of the end effector.

A SIMPLE EXAMPLE

To demonstrate the basic form of the kinematic equations used to describe the motion geometry of robotic manipulators, the following simple example will be used.

Consider a two-link arm moving in the X-Y plane as shown in Figure 1. The objective is to represent the position of the two links with respect to the base reference frame X-Y in terms of the joint angles θ_1 and θ_2. Using geometric relations, the coordinates of the ends of the links can simply be written as

$$X_1 = a_1\cos\theta_1 \qquad Y_1 = a_1\sin\theta_1 \tag{1}$$

$$X_2 = a_1\cos\theta_1 + a_2\cos(\theta_1 + \theta_2) \qquad Y_2 = a_1\sin\theta_1 + a_2\sin(\theta_1 + \theta_2) \tag{2}$$

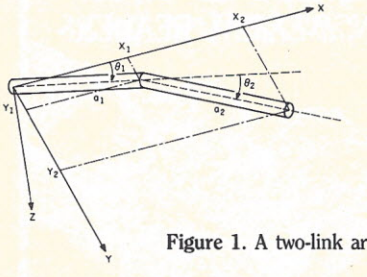


Figure 1. A two-link arm in an X-Y plane is shown.

Equations (1) and (2) are often referred to as the **forward** or **direct** kinematic equations, i.e., the position of the manipulator in Cartesian space given the joint angles. It is apparent from these equations that the calculation of the end effector position involves only a direct substitution of the joint angles. Furthermore, a unique solution is guaranteed for any set of physically attainable angles $\{\theta_1, \theta_2\}$.

Further examination of equations (1) and (2) indicates immediately the difficulties encountered in trying to solve for the joint angles given the Cartesian coordinates of the links. By rearranging equations (1) (or through observation of Figure 1) it can be deduced that

$$\theta_1 = \tan^{-1}\left(\frac{Y_1}{X_1}\right) \quad \text{with the constraint that} \quad X_1^2 + Y_1^2 = a_1^2 \tag{3}$$

thus representing a circle of radius a_1 with its center at the origin. Equation (3) is usually not of interest since coordinates (X_1, Y_1) seldom play a major role in the trajectory planning of the end effector. Therefore, a set of more useful relationships is that which relates individual joint angles to the end effector position (X_2, Y_2). The following two equations, derived using the cosine rule, perform that specific task

$$\theta_1 = \tan^{-1}\left(\frac{Y_2}{X_2}\right) - \tan^{-1}\left[\frac{a_2\sin\theta_2}{(a_1 + a_2\cos\theta_2)}\right] \tag{4}$$

$$\theta_2 = \cos^{-1}\frac{1}{2}\left[\frac{X_2^2 + Y_2^2 - (a_1^2 + a_2^2)}{a_1 a_2}\right] \tag{5}$$

in which θ_2 has to be solved for first, then substituted into (4) to obtain θ_1. These are known as the **inverse** kinematic equations.

By observation of these two equations, a constraint for the possible range of X_2 and Y_2 can be immediately formulated. Namely,

$$a_1 - a_2 \leqslant \sqrt{X_2^2 + Y_2^2} \leqslant a_1 + a_2 \tag{6}$$

Translated into words, equation (6) states that the workspace for the robot arm (Figure 2) has an outer envelope of $a_1 + a_2$ (both links extended) and an inner envelope of $a_1 - a_2$, applicable for $a_1 \geqslant a_2$ (both links overlapping).

An important fact about inverse kinematic equations is the nonexistence of a unique solution set when the end effector position falls within the workspace envelopes, i.e. when

$$a_1 - a_2 < \sqrt{X_2^2 + Y_2^2} < a_1 + a_2$$

This phenomenon gives rise to two distinct "postures," each depending on the quadrant from which θ_2 is chosen (Figure 3).

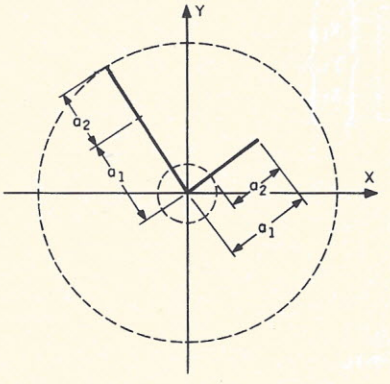


Figure 2. The robot's workspace has an outer envelope of $a_1 + a_2$ (both links extended) and an inner envelope of $a_1 - a_2$, applicable for $a_1 \geqslant a_2$ (both links overlapping).

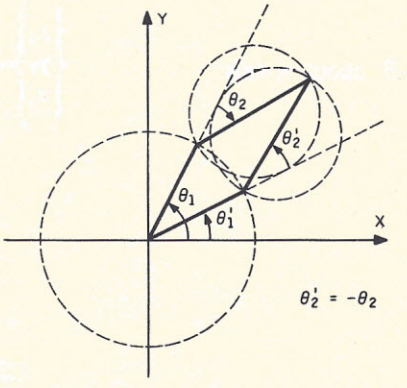


Figure 3. No unique solution set exists when the end effector position falls within the workspace envelopes. This results in two distinct "postures," each depending on the quadrant from which θ_2 is chosen.

HOMOGENEOUS LINK TRANSFORMATIONS

It is apparent from the previous example that the kinematic equations could become quite elaborate with the addition of one or more links. The approach used in deriving these equations is by no means systematic and could cause serious mathematical complexities, especially if the motion is in three dimensions. This problem was recognized many years ago by scientists in the field of computer graphics, and the result was the development and use of homogeneous transformation matrices.

A transform matrix is a 4 by 4 matrix, which, when multiplied by a vector describing an orthogonal coordinate system, changes its orientation and position in space. The question often arises as to why it is a 4 by 4 matrix, when the coordinate frame vector is only 3 by 1. To simplify the answer to this question, consider the following transformation

$$\begin{Bmatrix} x_2 \\ y_2 \\ z_2 \end{Bmatrix} = \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{bmatrix} \begin{Bmatrix} x_1 \\ y_1 \\ z_1 \end{Bmatrix}$$

This results in the three independent equations

$$\begin{aligned} x_2 &= a_1x_1 + b_1y_1 + c_1z_1 \\ y_2 &= a_2x_1 + b_2y_1 + c_2z_1 \\ z_2 &= a_3x_1 + b_3y_1 + c_3z_1 \end{aligned} \tag{7}$$

It is obvious from equations (7) that the vector $\{x_1\ y_1\ z_1\}$ can only be scaled or rotated by this 3 by 3 matrix. For example, if $a_2 = a_3 = b_1 = b_3 = c_1 = c_2 = 0$ then from (7)

$$\begin{aligned} x_2 &= a_1x_1 \\ y_2 &= b_2y_1 \\ z_2 &= c_3z_1 \end{aligned}$$

which is a scaling of the coordinate system by a constant value in each direction. Of course, if $a_1 = b_2 = c_3 = e$ (where e is some arbitrary constant), then the entire coordinate system is blown up or down by an amount e.

Rotation of a coordinate system by an angle θ about one of its axes is accomplished by projecting the other two axes on a rotated orthogonal triad (Figure 4), resulting in the following three direction cosine transformation matrices

for rotation θ_x about x_1 axis

$$\begin{Bmatrix} x_2 \\ y_2 \\ z_2 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix} \begin{Bmatrix} x_1 \\ y_1 \\ z_1 \end{Bmatrix}$$

for rotation θ_y about y_1 axis

$$\begin{Bmatrix} x_2 \\ y_2 \\ z_2 \end{Bmatrix} = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \begin{Bmatrix} x_1 \\ y_1 \\ z_1 \end{Bmatrix}$$

for rotation θ_z about z_1 axis.

$$\begin{Bmatrix} x_2 \\ y_2 \\ z_2 \end{Bmatrix} = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} x_1 \\ y_1 \\ z_1 \end{Bmatrix}$$

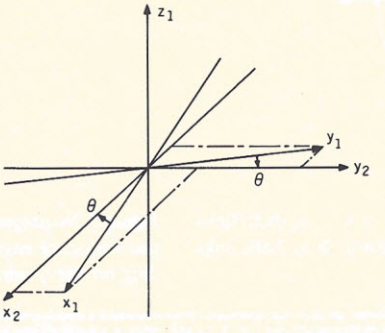


Figure 4. Rotation of a coordinate system by an angle θ about one of its axes is accomplished by projecting the other two axes on a rotated orthogonal triad.

To perform a translation of a vector in space by some constant amount, a 3 by 3 matrix no longer suffices. A coordinate frame can be moved to any point just by adding a constant value along its axes. For example, a vector $\{x_1\ y_1\ z_1\}^T$ can be translated by an amount $\{a\ b\ c\}^T$ using the transformation

$$\begin{aligned} x_2 &= x_1 + a \\ y_2 &= y_1 + b \\ z_2 &= z_1 + c \end{aligned} \tag{8}$$

Equations (8) can be represented in matrix form only if the vectors (or coordinates) $\{x_1\ y_1\ z_1\}^T$ and $\{x_2\ y_2\ z_2\}^T$ are written as homogeneous coordinates. The homogeneous coordinate representation of vectors in space associates, with each vector $\{X\ Y\ Z\}^T$, an ordered 4 by 1 vector $\{\overline{X}\ \overline{Y}\ \overline{Z}\ \overline{W}\}^T$, with $\overline{X}, \overline{Y}, \overline{Z}$ and $\overline{W}$ chosen so that $X = \overline{X}/\overline{W}$, $Y = \overline{Y}/\overline{W}$, and $Z = \overline{Z}/\overline{W}$. Therefore, a vector $\{2\ 1\ 3\}^T$ can be identified as $\{4\ 2\ 6\ 2\}^T$, or in normalized homogeneous representation, as $\{2\ 1\ 3\ 1\}^T$

Hence, equations (8) can now be displayed as

$$\begin{Bmatrix} x_2 \\ y_2 \\ z_2 \\ 1 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} x_1 \\ y_1 \\ z_1 \\ 1 \end{Bmatrix}$$

Furthermore, the transformation matrix that generated equations (7) can be expanded to a 4 by 4 matrix (without affecting its operation), resulting in

$$\begin{Bmatrix} x_2 \\ y_2 \\ z_2 \\ 1 \end{Bmatrix} = \begin{bmatrix} a & b & c & 0 \\ a & b & c & 0 \\ a & b & c & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} x_1 \\ y_1 \\ z_1 \\ 1 \end{Bmatrix}$$

It should be noted that the bottom row in the above fourth-order matrices contributes to perspective transformation and thus is never used in robot kinematics.

Successive translations and rotations can be combined into a single transformation matrix that will carry out the two operations in one step. This is accomplished by concatenating the individual matrices.

For robot manipulators, the first step is to set up the appropriate coordinate systems at each joint and at the base. The most commonly adopted convention (Paul) is to place the coordinate frame at the end of its respective link. All the consecutive reference frames would have a common post rotated direction for the x axis, and the z axis would be in the direction of motion of the next link (Figure 5).

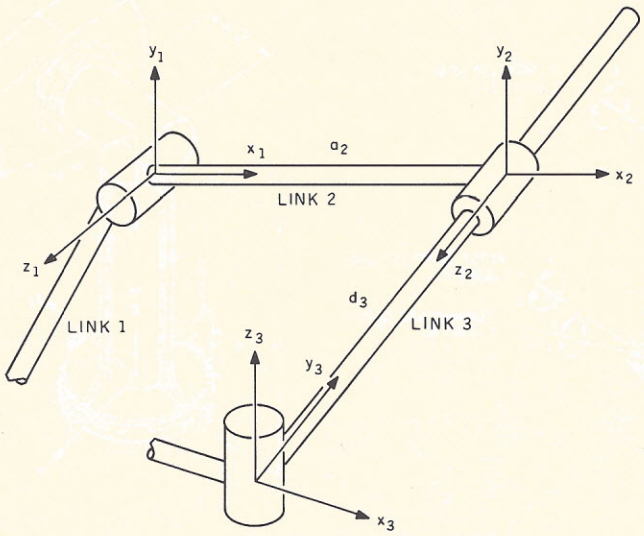


Figure 5. A robot manipulator with two convolute joints and one prismatic joint is shown.

Therefore, to transform from coordinate frame x_1, y_1, z_1 to x_2, y_2, z_2 the following series of transformations must be performed:

1. Rotate amount θ_2 about z_1;
2. Translate amount a_2 along x_2 which is the same as x_1;

and from x_2, y_2, z_2 to x_3, y_3, z_3.

1. Translate amount d_3 along z_2;
2. Rotate amount α_3 about x_3 which is the same as x_2.

The general set of transformations would thus include four consecutive operations (Paul), namely:

1. Rotate by θ_n about z_{n-1} (if revolute joint);
2. Translate by d_n along z_{n-1} (if prismatic joint);
3. Translate by a_n (constant length) along x_n;
4. Rotate by α_n about x_n.

These four homogeneous transformations result in the following matrix

$$A_n = \begin{bmatrix} \cos\theta_n & -\sin\theta_n \cos\alpha_n & \sin\theta_n \sin\alpha_n & a_n\cos\theta_n \\ \sin\theta_n & \cos\theta_n \cos\alpha_n & -\cos\theta_n \sin\alpha_n & a_n\sin\theta_n \\ 0 & \sin\alpha_n & \cos\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

from which the position of the end effector $\{\overline{P}\}_n$ relative to the base coordinate system $\{\overline{P}\}_o$ can be obtained as

$$\{\overline{P}\}_n = \overline{T}_n \{\overline{P}\}_o$$

where

$$\overline{T}_n = A_1 A_2 \ldots . A_{n-1} A_n$$

$$\{\overline{P}\}_n = \{x_n \; y_n \; z_n\}^T$$

$$\{\overline{P}\}_o = \{x_o \; y_o \; z_o\}^T$$

ANOTHER EXAMPLE

To demonstrate how the previous method is applied, consider, for example, the kinematics of a PUMA® 550 robot with its five axes of motion (Figures 6a and 6b). Matrix A_n can now be derived for each of the five axes. For the sake of clarity and completeness, an attempt will be made to show the rotations and translations between the reference frames.

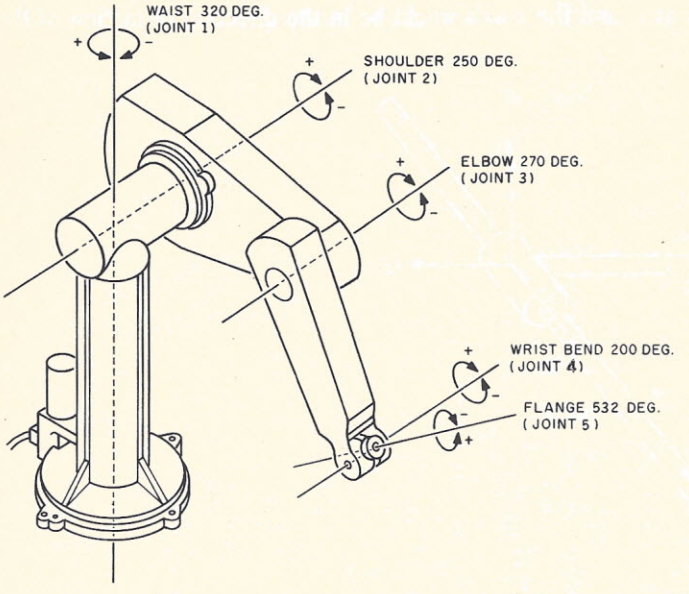


Figure 6a. The PUMA 550 has five axes of motion.

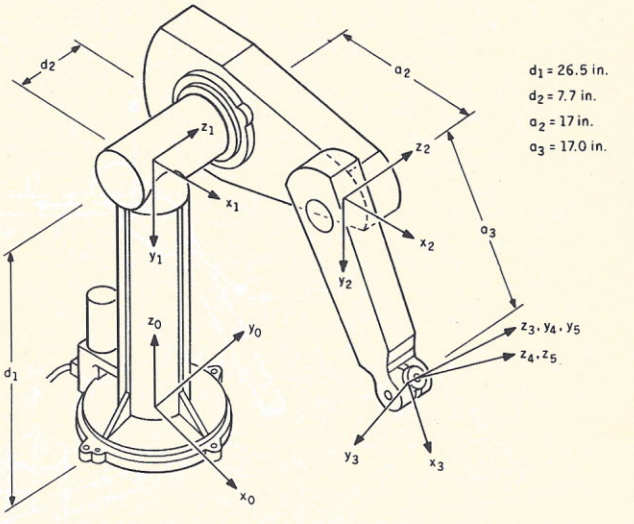


Figure 6b. Matrix A_n can be derived for each of the robot's five axes by a process of rotations and translations between the reference frames.

Frame 0 to frame 1:

1. Rotate by θ_1 about z_0—lines up x_0 with x_1;
2. Translate by d_1 along z_0—places origin of frame 0 onto origin of frame 1;
3. Rotate by -90 degrees about x_1 (or x_0)—frame 0 is now lined up with frame 1.

$$\Rightarrow \theta_n=\theta_1 \quad d_n=d_1=26.5 \text{ in.} \quad a_n=0 \quad \alpha_n=\alpha_1=-90 \text{ degrees}$$

$$A_1 = \begin{bmatrix} \cos\theta_1 & 0 & -\sin\theta_1 & 0 \\ \sin\theta_1 & 0 & \cos\theta_1 & 0 \\ 0 & -1 & 0 & 26.5 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Frame 1 to frame 2:

1. Rotate by θ_2 about z_1—lines up x_1 with x_2;
2. Translate by d_2 along z_1, then translate by a_2 along x_2 (or x_1)—places origin of frame 1 onto origin of frame 2 and both frames are lined up.

$$\Rightarrow \theta_n=\theta_2 \quad d_n=d_2=7.7 \text{ in.} \quad a_n=a_2=17.0 \text{ in.} \quad \alpha_n=0 \text{ degrees}$$

$$A_2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 17.0\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & 17.0\sin\theta_2 \\ 0 & 0 & 1 & 7.7 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Frame 2 to frame 3:

1. Rotate by θ_3 about z_2—lines up x_2 with x_3;
2. Translate by a_3 along x_3 (or x_2)—places origin of frame 2 onto origin of frame 3 and both frames are lined up.

$$\Rightarrow \theta_n=\theta_3 \quad d_n=0 \quad a_n=a_3=17.1 \text{ in.} \quad \alpha_n=0 \text{ degrees}$$

$$A_3 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & 17.1\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & 17.1\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Frame 3 to frame 4:

1. Rotate by θ_4 about z_3—lines up x_3 with x_4;
2. Rotate by 90 degrees about x_3 (or x_4)—lines up frame 3 with frame 4.

$$\Rightarrow \theta_n=\theta_4 \quad d_n=0 \quad a_n=0 \quad \alpha_n=90 \text{ degrees}$$

$$A_4 = \begin{bmatrix} \cos\theta_4 & 0 & \sin\theta_4 & 0 \\ \sin\theta_4 & 0 & -\cos\theta_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Frame 4 to frame 5:

1. Rotate by θ_5 about z_4—lines up x_4 with x_5 and thus both reference frames.

$$\Rightarrow \theta_n=\theta_5 \quad d_n=0 \quad a_n=0 \quad \alpha_n=0 \text{ degrees}$$

$$A_5 = \begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & 0 \\ \sin\theta_5 & \cos\theta_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Therefore, the description of the end of the manipulator, link coordinate frame 5, with respect to the base coordinate frame is

$$\overline{T}_6 = A_1A_2A_3A_4A_5$$

or

$$\overline{T}_6 = \begin{bmatrix} t_{11} & t_{12} & t_{13} & t_{14} \\ t_{21} & t_{22} & t_{23} & t_{24} \\ t_{31} & t_{32} & t_{33} & t_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where

$$t_{11} = c_1c_2c_3c_4c_5 - c_1c_2s_3s_4c_5 - c_1s_2s_3c_4c_5 - c_1s_2c_3s_4c_5 - s_1s_5$$

$$t_{12} = c_1c_2c_3s_4c_5 + c_1c_2s_3s_4s_5 + c_1s_2s_3s_4c_5 + c_1s_2c_3s_4s_5 - s_1c_5$$

$$t_{13} = c_1c_2s_3s_4 + c_1c_2s_3c_4 - c_1s_2s_3s_4 + c_1s_2c_3c_4$$

$$t_{14} = c_1c_2a_3c_3 - c_1s_2a_3s_3 + c_1a_2c_2 - s_1d_2$$

$$t_{21} = s_1c_2c_3c_4c_5 - s_1c_2s_3s_4c_5 - s_1s_2s_3c_4c_5 - s_1s_2c_3s_4c_5 + c_1s_5$$

$$t_{22} = s_1c_2s_3s_4s_5 - s_1c_2c_3s_4c_5 + s_1s_2s_3s_4c_5 + s_1s_2c_3s_4s_5 + c_1c_5$$

$$t_{23} = s_1c_2s_3s_4 + s_1c_2s_3c_4 - s_1s_2s_3s_4 + s_1s_2c_3c_4$$

$$t_{24} = s_1c_2a_3c_3 - s_1s_2a_3s_3 + s_1a_2c_2 + c_1d_2$$

$$t_{31} = s_2s_3s_4c_5 - s_2c_3c_4c_5 - c_2s_3c_4c_5 - c_2c_3s_4c_5$$

$$t_{32} = s_2c_3s_4c_5 - s_2s_3s_4s_5 + c_2s_3s_4c_5 + c_2c_3s_4s_5$$

$$t_{33} = c_2c_3c_4 - s_2c_3s_4 - s_2c_3c_4 - c_2s_3s_4$$

$$t_{34} = d_1 - s_2a_3c_3 - c_2a_3s_3 - a_2s_2$$

THE EDITORS OF SENSORS MAGAZINE AND THE COMPANIES BELOW INVITE YOU TO JOIN THEM IN THE FIRST NATIONAL CONFERENCE AND EXPOSITION DEVOTED *EXCLUSIVELY* TO SENSOR AND TRANSDUCER TECHNOLOGY.

Aleph International ■ Amerace Corporation ■ Azonics Corp. ■ BLH Electronics ■ Bruel & Kjaer Instruments ■ Campbell Scientific Incorporated ■ Crystal Technology, Inc. ■ Druck Incorporated ■ Dynisco ■ Eaton Corporation Automation Products Div. ■ Eaton Corporation Cutler Hammer Products ■ Elmwood Sensors ■ Endevco Div., Becton, Dickinson & Company ■ Hottinger Baldwin Measurements ■ Hy-Cal Engineering Unit of General Signal ■ International Electro-Magnetics ■ Kaman Instrumentation ■ Kistler Instrument ■ Massa Products Corporation ■ Migatron Corporation ■ Mikron Instruments ■ Molytek, Inc. ■ Namco Controls ■ Motorola Semiconductor ■ Omron Electronics ■ Opcon Inc. ■ Optical Technologies Inc. ■ Paine Instruments ■ PCB Piezotronics, Inc. ■ Pennwalt Corporation ■ Physical Acoustics Corp. ■ Polaroid Corporation ■ Precise Sensors, Inc. ■ Pulsotronic Merten GmbH and Co., KG ■ Raytek, Inc. ■ Rechner Electronics Industries, Inc. ■ Saab Systems Inc. ■ Sangamo, Div. of Solartron Transducers ■ Scanivalve Corporation ■ Sencon Inc. ■ Sensing Devices Inc. ■ Sensor Developments, Inc. ■ Sensotec, Inc. ■ Sensym, Inc. ■ Setra Systems Inc. ■ Sick Optik-Elektronik Inc. ■ Smith Research & Technology ■ Spectron Glass & Electronics ■ Sperry Sensing Systems ■ Thunder Scientific Corp. ■ Transamerica Delaval Inc./CEC Instruments Division ■ Tri-Tronics Inc. ■ Turck Multiprox, Inc. ■ Universal Flow Monitors ■ Validyne Engineering ■ Viatran Corporation ■ Vibro-Meter Corporation ■ Xolox Corporation ■ Yellow Springs Instrument Company Inc. ■ Pepperl & Fuchs, Inc. ■ R.M. Young Company

* Exhibitors as of January 10, 1986

SENSORS EXPO

O'HARE EXPOSITION CENTER, CHICAGO
SEPTEMBER 17 – 19, 1986

The response to SENSORS EXPO — the first conference and exposition devoted exclusively to sensor and transducer technology — has been enthusiastic on all counts.

A Call for Papers in this magazine produced a deluge of submissions from industry experts —papers reflecting the ever-increasing role of sensors in reshaping manufacturing, processing, materials handling, research and development, quality assurance, and robotics.

Inquiries for information on the program of professional education — currently being shaped by the editors of Sensors magazine — have been pouring in from design engineers, engineering and R&D managers, scientists, manufacturing and production executives, and corporate managers...

...decision-makers from industries including: automotive, aerospace and aviation, agriculture, communications, computers, consumer electronics, defense, food processing, heavy industry, medical device and instrumentation, petrochemicals, pharmaceuticals, and more.

This first-of-its-kind opportunity to reach the specifiers and buyers who are designing and developing products and systems with electronic sensing capability has also attracted many supplier companies, with many more to come.

SENSORS EXPO offers three days of learning — at the conference program, in the exhibit hall, and in the many informal exchanges with your colleagues from all parts of the country.

If you'd like more information about attending, circle the appropriate Reader Service Inquiry number below. The complete program will be sent to you as soon as it's available.

Or, if you'd like the opportunity to exhibit, face-to-face, to thousands of engineering, manufacturing, and production specifiers, circling the second Reader Service Inquiry number will get you a complete Exhibitor Package.

For further information about SENSORS EXPO, contact Susan Reuter at

Expocon Management Associates, Inc.
3695 Post Road
Southport, CT 06490
(203) 259-5734

For information on Attending, Circle 43
For information on Exhibiting, Circle 44

and

$$s_i = \sin\theta_i$$
$$c_i = \cos\theta_i$$

for $i = 1,2,3,4,5$

The position of the end effector can now be described as

$$\begin{Bmatrix} \overline{X}_5 \\ \overline{Y}_5 \\ \overline{Z}_5 \\ 1 \end{Bmatrix} = \begin{bmatrix} t_{11} & t_{12} & t_{13} & t_{14} \\ t_{21} & t_{22} & t_{23} & t_{24} \\ t_{31} & t_{32} & t_{33} & t_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \overline{X}_o \\ \overline{Y}_o \\ \overline{Z}_o \\ 1 \end{Bmatrix}$$

A major simplification can be achieved if the base coordinates are assumed to be (0,0,0), from which

$$\begin{aligned} \overline{X}_5 &= t_{14} \\ \overline{Y}_5 &= t_{24} \\ \overline{Z}_5 &= t_{34} \end{aligned} \tag{10}$$

for any combination of angles $\theta_1,\ldots,\theta_5$.

From these equations, the home position can be easily derived by setting $\theta_i = 0$ for $i = 1,\ldots,5$ or, $s_i = 0$, $c_i = 1$ for $i = 1,\ldots,5$, thus resulting in

$$\begin{aligned} \overline{X}_5 &= a_2 + a_3 = 34.1 \text{ in.} \\ \overline{Y}_5 &= d_2 = 7.7 \text{ in.} \\ \overline{Z}_5 &= d_1 = 26.5 \text{ in.} \end{aligned}$$

It should be noted that the wrist and flange angles θ_4 and θ_5 are not included in equations (10), since all they do is contribute to the orientation of the end effector and not its position in space. These two angles play a role when a gripper or tool is attached to the flange. The tip of the tool would be related to the wrist through a transformation A_6 from which its description relative to the base coordinates would be given by

$$\overline{T}_6 = \overline{T}_5 A_6$$

It is apparent from the previous derivations that the inverse kinematics problem would not be trivial. Given a point in space, two sets of angles θ_2, θ_3 could satisfy the solution (of course, θ_1 is unique), and for each set, there could exist a combination of angles θ_4 and θ_5.

Because no unique set of joint angles for a given path can be obtained, accurately planning a trajectory for a multilink robot arm can be quite difficult. Very small step sizes are often necessary to eliminate sudden extreme posture changes due to a "flipping effect" between two quadrants. These and other problems ensure that the discipline of arm kinematics will continue to receive the research community's attention for quite some time.

BIBLIOGRAPHY

1. Asada, H. *A Characteristic Analysis of Manipulator Dynamics Using Principal Transformations*. Proceedings, American Control Conference, Washington, DC, June 1982.
2. Brady, M. et al. *Robot Motion: Planning and Control*. MIT Press, Cambridge, MA, 1982.
3. Myers, R.E. *Microcomputer Graphics*. Addison Wesley Publishing Co., Reading, MA, 1982.
4. Paul, R.P. *Robot Manipulators: Mathematics, Programming, and Control*. MIT Press, Cambridge, MA, 1981.
5. Roberts, L.G. *Homogeneous Matrix Representation of Three-Dimensional Solids*. Lincoln Laboratory, MIT, Report No. 315, 1963.
6. Torby, B.J. *Advanced Dynamics for Engineers*. Holt, Rinehart, and Winston, New York, NY, 1984.

Nabih E. Bedewi is President of Applied Engineering Research, Inc. and a Ph.D. candidate in mechanical engineering at the University of Maryland.

Reader Feedback

To rate this article, circle the appropriate number on the Reader Service card.

3	13	23
Excellent	Good	Fair

Robots Prove Themselves in a Small Shop

Peter C. Doyle

Flexible automation, initially found only in very large scale operations, has begun to prove cost-effective in the smaller shops as well. When in January 1984 Consolidated Coating Company, Inc. of Hopedale, Massachusetts installed a DeVilbiss TR 3500, the company became the first independent, nondedicated, finishing facility to use a spray painting robot. The experiment paid off so well that last October Consolidated bought and put on line three DeVilbiss 450s.

Consolidated Coating was founded in 1979 by co-owners John Hughes and John Mattson. The startup was their response to a rising demand for finishing facilities, a market created by new firms in the region that were manufacturing computers and other electronic equipment faster than the local finishing shops could turn out housings for them. Consolidated's list of customers came to include companies such as Allen Test Products, Computervision, Data Terminal Systems, Technicon, and Wang.

Getting Started. The firm looked to robotics for two reasons. As Mattson put it, "We wanted to increase productivity, but we also wanted to use robotics as a marketing tool. We thought it would be a way to attract new business because at that time there were not many robots in use around the country, and there were none in small finishing operations such as ours."

The first robot was a success. "The quality of the finish was very high," Mattson said, "and it was absolutely the same on every single part. So, not only did we get an increase in productivity, we got a dramatic decrease in rejects. This equates to more parts out the door and a better bottom line." According to Hughes, "Savings occur because of the robots' repeatability. The human worker, no matter how good he is, will get tired. He'll start to make wider overlaps or spray off the part. Over many hundreds of parts, it ends up being a very big [paint] savings."

We wanted to increase productivity, but we also wanted to use robotics as a marketing tool, a way to attract new business. There were no robots in small finishing operations such as ours.

Paint savings depend also on part size and can range from 10 to 15 percent, with the greatest savings on larger parts. There are savings in the salary department too, for an experienced spray painter makes $10 an hour. Consolidated was therefore able to give its customers lower bids, which meant more business. Although unwilling to discuss the specifics of the firm's bidding process because of zealous competition, Mattson did say that his prices were "very competitive, as a result of the robots."

In selecting a robot, Mattson said, "Our main concern was flexibility. Most of the units we saw in operation were used in large-volume, dedicated situations. We needed a robot that could spray paint 1000 of one unit, perhaps a box with five planes, and then be able to quickly switch over to a box having 28 planes. Also, we had to be able to use the robot efficiently. It's nice to be able to tell people you have a robot, but if you can't use them, they're like an anchor."

Consolidated chose the DeVilbiss TR 3500 for several reasons. Mattson pointed to his firm's prior business with DeVilbiss, knowing the people there, and the quality of the equipment and service. DeVilbiss,

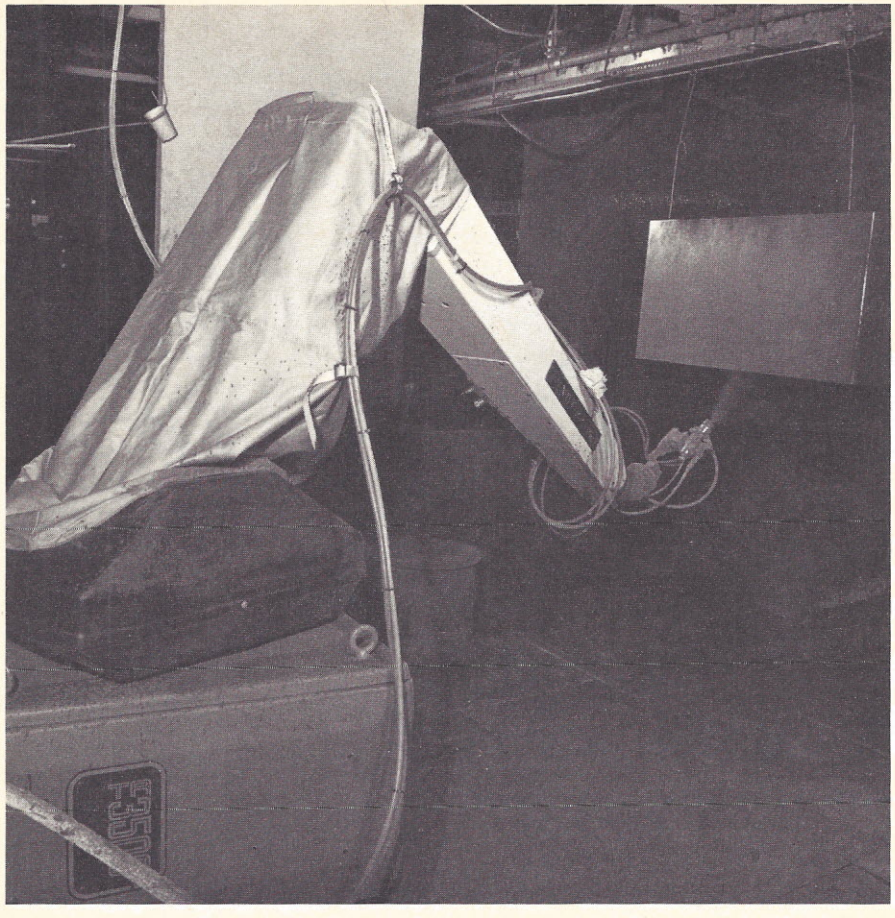


Photo 1. The TR 3500 six-axis robot is shown spray painting half of a two-part cabinet designed to house automobile emissions test equipment. The robot's flexibility allows it to paint both the inside and the outside of the cabinet.

he said, offered "the Cadillac of the industry." Purchase, installation, and accessories for the TR 3500 amounted to about $100,000, but the three TR 450s cost "considerably less," Mattson said. The TR 450, one of the smaller members of the DeVilbiss line, is a five-axis hydraulic robot with a 530 lb. arm and a maximum speed of 5.5 ft/sec. The TR 3500, still in use, is a heavier duty hydraulic machine with six axes and a 1000 lb. arm (Photo 1).

Programming the Robot. It would be pointless to gain production efficiency from a robot only to lose time in setup for a new finishing operation. Accordingly, one important element of robot selection is ease of programming. For Consolidated, this relatively easy task requires no more than about 10 minutes. The programming process, or training the robot, is a straightforward operation, and once a program is loaded it is ready to run. Ken Close, DeVilbiss's finishing automation specialist, described the process. "First the computer is placed in the training mode and two handles are installed on the robot arm. These handles enable the programmer to guide the robot through a particular spraying process. Each movement and function is stored in the computer's memory. A movement is the actual left and right, up and down motion. A function might be to trigger the spray gun or activate the gun flipper, which changes the direction of the spray nozzle.

The robot's wrist has a range of 176 degrees. Activating the flipper provides an additional 90 degrees, essential when the robot has to spray a hard-to-reach area, such as behind a flange. Parts to be spray painted are defined in terms of their planes. Each approach a robot must make constitutes a plane. Examples include each side of a box, along with every groove, bevel, or protuberance to be finished. The

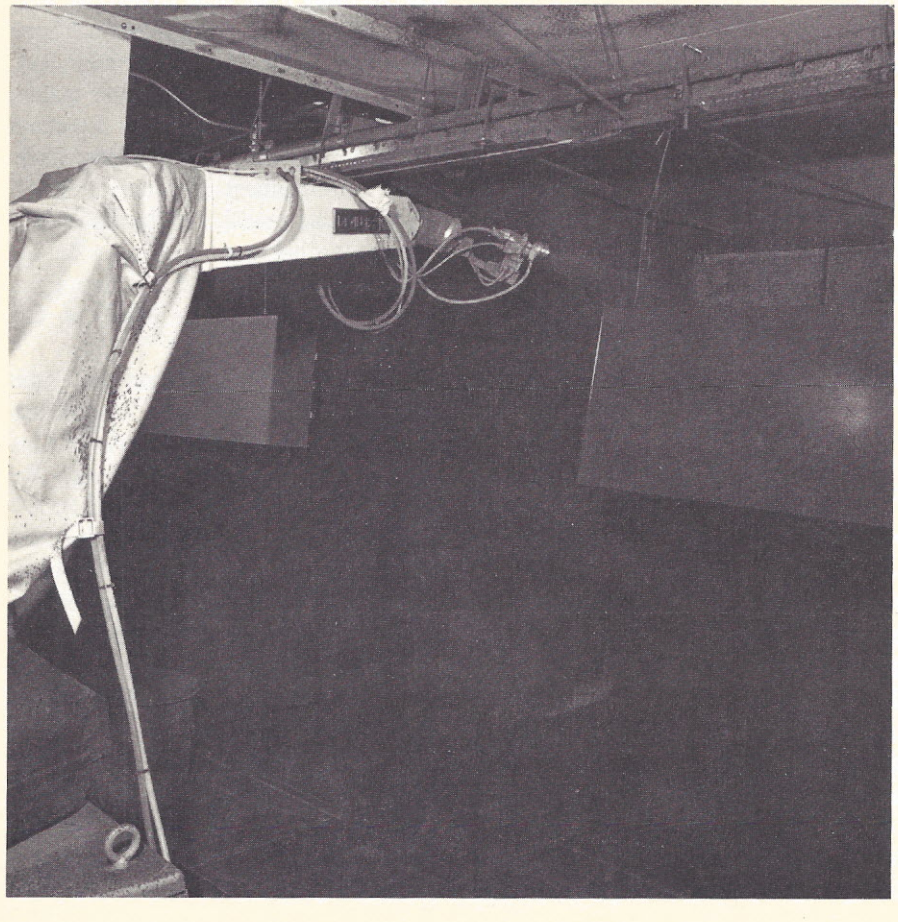


Photo 2. Each robot is equipped with an electric eye that senses parts as they move along the conveyor and initiates the spraying operation.

robot arm sometimes must make more than one pass to cover a plane's entire surface.

The Paint Line. Consolidated's workers were recently observed as they prepared to finish a two-part cabinet designed to house automobile emissions test equipment. The cabinet parts had previously been sprayed with an electromagnetic/radio frequency interference shielding. In this setup, the first robot was to apply a smooth coat to the inside of a cabinet part; the second robot, a smooth coat to the outside; and the third, a texture coat to the outside.

The three TR 450s are connected to a 250-foot overhead conveyor system, from which the parts hang in set positions. When a part arrives at a robot, it is sensed by an electric eye and spraying begins (Photo 2). Depending on part complexity, spraying can take anywhere from 10 to 90 seconds. The length of the conveyor between robots allows the parts to dry during travel. Parts drying is particularly important when a texture coat is to be applied over a smooth coat. "Flash off," the time it takes for a part to become tacky but not dry, the point at which most of the solvents have evaporated from the paint, requires approximately 25 minutes. The texture coat can be applied at that point. An alternative to the long conveyor system would be to install drying ovens between robots, Hughes said.

Fewer skilled workers were needed for painting but more support personnel were required to keep up with the robots' increased output.

Changes—Past and Future. Automation at Consolidated brought with it some personnel changes, but the effects were felt in distribution, rather than in number of employees. The firm employed 30 workers before automating, and the work force still stands at 30. With only seven booths for manual spraying, fewer skilled workers were needed for painting but more support personnel were required to keep up with the robots' increased output—workers to load and remove parts from the line, inspectors, and packers. The firm has grown at a rate of about 45 percent each year. It is currently leasing 100,000 square feet of space on the fourth floor of a huge factory where textile equipment was once manufactured, but a move is in the offing and site plan work for a new facility in nearby Bellingham, Massachusetts is under way. Consolidated will have less space in the new plant, but it will be space used more efficiently. The work environment will be cleaner—and probably shared by more robots.

Reader Feedback

To rate this article, circle the appropriate number on the Reader Service card.

4	14	24
Excellent	Good	Fair

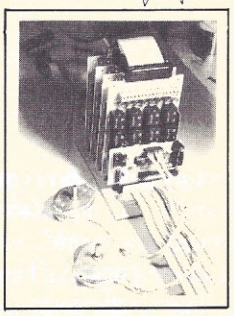
The Amazing A-BUS

NEW

Hobbyists, Engineers, Scientists, OEMs, and universities, the A-BUS is for you!

What is the A-BUS? The A-BUS is the best way to connect a variety of **Input** and **Output** cards (such as analog converters, relays, sensors, motor controllers, etc.) to *your* computer.

A typical **A-BUS** system consists of: • An Adapter Card and a Cable to convert your computer to the **A-BUS** standard • The **A-BUS** motherboard, with several slots in which you plug the different Input and Output cards • Your choice of cards listed below to fit your application. (Many more cards will be released soon.)



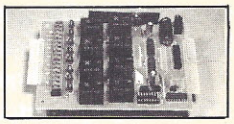
The "A" stands for Amazing, and here is why:

The **A-BUS** is designed to work with many different computers: IBM PC,XT,AT; Apple II's; and TRS-80 Models I,III,4,4P,4D,100,1000. Should you ever move to another system, your investment is protected. Only the low cost adapter card has to be changed!

The system is expandable to meet current and future needs easily. Motherboards can be daisy chained for up to 20 cards.

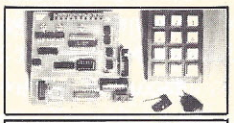
Low cost and reliability will ensure your project success.

A-BUS Adapter for IBM's and compatibles. Uses one short slot AR-133...$69
A-BUS Adapter for Model I Plugs into 40-pin I/O card edge (on KB or E/I) AR-131...$39
A-BUS Adapter for Models 3,4,4P,4D Plugs into 50-pin I/O bus. AR-132...$49
CABLE (3 ft.) to connect computer to **A-BUS**. One required for each system. CA-163...$29
A-BUS Motherboard, for up to 5 cards (not needed if using only one card) Includes sturdy anodized aluminum frame and card guides. MB-120...$95
MANUAL All the **A-BUS** products include a detailed user's manual.



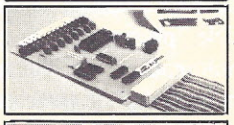
A-BUS Relay Card: RE-140...$129

This industrial grade output card includes 8 relays. (Contact rated 3 Amp @ 125V) All the decoding necessary is included which means that you can connect up to 64 cards (which is 512 relays.) Easily controlled using "OUT" commands. For example OUT 1,0 turns all the relays off on card #1. Eight LED's show the states of the relays.



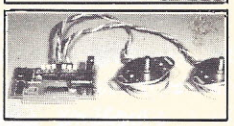
A-BUS Isolated Digital Input Card: IN-141...$49

This optically isolated input card makes it safe and easy to connect external devices (switches, thermostats, keypads) to your computer. Simple INP commands read the status (ON or OFF) of the eight inputs. Inputs can be Voltage (5-24V), Current (5-10mA), or switch closure. Full address decoding allows up to 64 input cards (that's 512 channels) per computer.



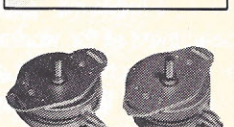
A-BUS Analog Input Card: AD-142...$119

8 channel 8 bit Analog to Digital converter. Your computer can read voltages, temperatures, pressures, light levels, etc. • Input range: 0 to 5.1 Volts. • Resolution: 20mV. • Conversion time: 120 microseconds. In BASIC, you can take up to 100 readings per second. • Port address: selectable. Up to 64 Analog-80's can be connected to your computer for a total of 512 channels!
An optional Amplifier board can be added to read millivolts: AM-169 ..... $29



A-BUS Dual Stepper Controller: ST-143...$69

Don't be afraid of stepper motors anymore. The special package (below) includes everything you need to get familiar with steppers: • Controller card drives 2 steppers (12V bidirectional) ST-143...$69 • Stepper: 48 steps per revolution, up to 300 steps/second, ¼" shaft. MO-103...$15 • Power supply PS-126...$10
Special Package: Controller, *two* steppers and power supply: PA-181.....$99



SPECIAL Steppers: MO-103...4 for $39

12V, unipolar, 7.5°, 36 ohms, ¼" shaft, 300 steps/second. Copal mfg model SP-57, same as Airpax K82701-P2. Regularly $15 each.

A-BUS Prototyping card: PR-152...$14

Protocard is 3½ by 4½ inches, and will accept up to 10 IC's

CABLES: Standard and Custom

Send for our standard cable flyer and our worksheet for custom cables.

SPECIAL 4 for $39

ALPHA Products
79 04A Jamaica Ave., Woodhaven, NY 11421

800-221-0916
Orders Only. NY& info call (718) 296-5916
Hours: 9-5 Eastern Time

Add $3.00 per order for shipping. We accept Visa, MC, checks, M.O. C.O.D. add $3.00 extra. N.Y. residents add sales tax. Shipping to Canada is $5.00 Overseas, FPO, APO add 10%

Undesirable Environments: A Basis for Automation

Venkitaswamy Raju
Rochester Institute of Technology
Manufacturing Engineering Technology
PO Box 9887
Rochester, NY 14623-0887

Factory automation continues to be a top priority in manufacturing companies around the world, whether it involves employing material handling robots or installing totally computer integrated flexible manufacturing systems. Automation decisions traditionally have been based on such criteria as technology, market conditions, cost considerations, productivity, and manpower availability. Recent developments indicate that an undesirable manufacturing environment has also become a reason for automating. This article presents a method for making automation decisions based on the manufacturing environment.

"Manufacturing environment" refers to the operating conditions under which various operations are performed. Plant floor conditions usually include the cleanliness of the working area, cleanliness of the air in the working area, atmospheric conditions, lighting conditions, temperature in the working area, condition of the machines, nature of the raw material, and the hazards involved in handling the material and operating the machines. If the operating conditions in a manufacturing facility create an undesirable working environment, worker productivity in the facility will be adversely affected. The solution in such cases is either to improve the operating conditions or to automate the facility.

If the operating conditions in a manufacturing facility create an undesirable working environment, worker productivity will be adversely affected.

Table 1
The Operating Conditions

Operating condition	Weight factor
Mental strain	7
Accident risk	6
Poisonous gas	6
Radioactive material	6
Monotony	5
Third-shift operation	5
Noise	4
Muscular strain	4
Dust/dirt	3
Heat	3
Wetness	2
Vapors	2
Lack of light	2
Chemicals	2
Vibrations	2
Second-shift operation	1
Heavy safety clothing	1
Lack of ventilation	1

A METHOD FOR MAKING AUTOMATION DECISIONS

The method described here involves determining the state of the operating conditions that adversely affect workers. The process involves two steps. The first step is to calculate the impact of the operating conditions on manpower and the second is to decide whether to select or reject an automated system, based on the total impact of the operating conditions.

Calculating the impact of the operating conditions involves four steps. In the first step, each condition is assigned a weight factor. This is a purely subjective process in which the only consideration is the operating conditions' relative importance with respect to the human working environment. Table 1 lists the 18 operating conditions under consideration and their respective weight factors. It is by no means a comprehensive list, but the conditions listed represent the basic manufacturing environment in a plant. Mental strain is given the highest weight because it is usually associated with situations in which an operator must be alert at all times, gather information, process the informa-

tion mentally, make decisions, and implement those decisions instantaneously. The weights assigned to the other conditions in the list are only relative weights.

The second step in the process involves determining the level of impact of each of the operating conditions in a given manufacturing facility. Four levels are identified: "no impact," "low impact," "medium impact," and "high impact." The third step involves determining the weighted impact of the operating conditions on workers. This is done by multiplying the level of impact by the weight factor of the operating condition (weighted impact = level of impact × weight of the operating condition). The fourth step involves calculating the total impact of all the operating conditions. This is done by adding the weighted impact for the operating conditions. Table 2 shows the procedure used in calculating the total impact of the operating conditions.

The total impact calculations lead to the second step in the decision-making process: deciding whether to accept or to reject automation on the basis of the following guidelines:

- If the total impact of the operating conditions is equal to or below 62, the decision should be to reject automation. The limit is derived as follows: 186 divided by 3, multiplied by 1, equals 62. The number 3 represents the highest level of impact, and 186 is the total of maximum impacts.
- If the total impact of the operating conditions is above 124, then the decision should be to accept automation. The limit is derived as follows: 186 divided by 3, multiplied by 2, equals 124, with 3 representing the highest level of impact and 186 the total of maximum impacts.
- If the total impact of the operating conditions falls above 62 but does not exceed 124, then automation should be accepted conditionally.

AN EXAMPLE OF THE METHOD

To demonstrate the applicability of the method, data gathered from a study of a machine shop with manual punch presses was used. The shop operated three shifts a day. The operators performed simple and routine operations in making the parts. The job was basically a monotonous one. Because of the type of machines employed, there was a certain amount of vibration in the work area.

Table 2
Impact of the Operating Conditions

Operating Condition	Weight Factor	Level of Impact				Weighted Impact	Maximum Impact
		none = 0	low = 1	medium = 2	high = 3		
Mental strain	7	•				0	21
Accident risk	6		•			6	18
Poisonous gas	6	•				0	18
Radioactive material	6	•				0	18
Monotony	5				•	15	15
Third-shift Operation	5				•	15	15
Noise	4				•	12	12
Muscular strain	4		•			4	12
Dust/Dirt	3		•			3	9
Heat	3	•				0	9
Wetness	2	•				0	6
Vapors	2	•				0	6
Lack of light	2		•			2	6
Chemicals	2		•			2	6
Vibrations	2		•			2	6
Second-shift operation	1	•				0	3
Heavy safety clothing	1	•				0	3
Lack of ventilation	1	•				0	3
				Total		61	186

The application of the method is illustrated in Table 2. The level of impact of each of the operating conditions is indicated thus: •. The calculated values of the weighted impact are shown in column 7. The total impact for the example has a value of 61. According to the guidelines, this falls in the region where automation is not appropriate.

APPLYING THE METHOD

By employing the following procedure, the method described in this paper can be easily adapted to suit any type of manufacturing facility:

1. Form a team consisting of engineers and managers.
2. Let the team determine the operating conditions existing in the facility and assign a weight factor to each condition. Use Table 1 as a guide.
3. Let the team determine the level of impact of each of the operating conditions, using 0 for no impact, 1 for low impact, 2 for medium impact, and 3 for high impact.
4. Calculate the total maximum impact. Use Table 2 as a guide.
5. Set decision limits following the guidelines specified in the paper.
6. Calculate the weighted impact for each of the operating conditions.
7. Determine the total weighted impact for the facility.
8. Make the automation decision according to the guidelines.

The method described here is only one of many available for automation decisions. It takes into account the overall effect of the manufacturing environment on manpower but it is not a substitute for other methods based on such factors as technology or cost and it should be therefore treated as a supplementary procedure for automation decisions. It is important to note that this approach is based purely on subjective ratings of the operating conditions. But until there are better methods available for evaluating the impact of such factors as mental strain and accident risk, a subjective analysis is an acceptable alternative.

The author would like to thank professors L. Gennaro and J. Shealy.

Dr. Venkitaswamy Raju is a Professor of Manufacturing Engineering Technology at the Rochester Institute of Technology.

Reader Feedback

To rate this article, circle the appropriate number on the Reader Service card.

5	15	25
Excellent	Good	Fair

A Microcomputer Vision and Ranging System

Volker Petersen and John C. Even, Jr.
Iowa State University
Department of Industrial Engineering
212 Marston Hall
Ames, Iowa 50011

Machine vision systems will be finding more and more applications in industry over the next few years, and specifically in robotics applications. Forecasts predict that 25 percent of all robots sold in the United States by 1990 will have vision capability (1). With the world trend toward computer integrated manufacturing (CIM) and flexible manufacturing systems (FMS), today's robots need sensory feedback information, e.g., vision, tactile, or ranging systems, to be able to adapt to changes in their work environments.

The first machine vision systems were introduced in the late 1970s; today, a wide variety of machine vision systems are on the market. All of these systems, however, have a rather high price tag. A literature survey (2) shows a price range from $10,000 to $120,000 for commercially available vision systems.

At the Manufacturing Automation Laboratory of Iowa State University, we have developed a microcomputer-based, low-cost binary vision system that incorporates a ranging system. The use of a sonic ranging module to determine the distance between the camera and an object enables the normalization of the image information. The system is based on a 16-bit microprocessor microcomputer. Although slower than special-purpose machine vision equipment, this approach provides valuable vision capabilities for a wide range of applications. The low price (compared to commercially available systems) allows the implementation of a vision system in applications for which the cost of a full-scale machine vision system cannot be justified. The following assumptions apply to this system:

- Only binary images are used by the system to limit the amount of data processed and to keep the processing times short. In many applications, however, the designer can structure the environment to control the viewing conditions and to ensure sufficient contrast. Under these circumstances, binary vision can be used quite effectively.
- The scope is limited to geometrically regular workpieces. This restriction allows the use of descriptive figures, which are based on the geometric shape of each part, for identification.
- The images to be analyzed do not contain overlapping parts. This restriction allows the use of blob-analysis algorithms (3,4,5) instead of the more complex feature-based pattern recognition algorithms (6,7).

HARDWARE DESCRIPTION

The camera used in this project is a MicronEye camera built by Micron Technology, Inc. (8). For an imaging device, the camera uses the IS32 OpticRAM chip, which contains two 128 by 256 pixel arrays separated by a narrow strip. The manufacturer advises using only the pixels from the even-numbered rows and columns because the image needs to be enhanced via a software routine if all pixels are to be used. The latter option was not considered for this research since it would have increased the image processing time considerably. Thus, the camera resolution used was either 64 by 128 pixels or 128 by 128 pixels if both arrays were used. The camera is interfaced directly to an IBM PC or compatible microcomputer.

The camera can also be interfaced to any computer with an RS-232 port, but this option has the disadvantage of relatively slow image transmission rates. The selection of the MicronEye camera eliminated the need for an image digitizer and a frame grabber, which are commonly used to preprocess standard analog camera information for computer processing. The camera can produce two to five frames per second in typical room lighting and can achieve a maximum operating speed of 15 frames per second if only 64 by 128 pixels out of a full frame are used.

The ultrasonic ranging system chosen for this project is the Texas Instruments module SN28827, an updated version of the model used in the Polaroid SX-70 camera (9). This unit is inexpensive and fairly accurate, within ± 2 percent in a range between 1.33 and 35 ft, in measuring the distance between the camera and an object.

The microcomputer chosen was an IBM AT; an 80287 (8087) mathematical coprocessor was added to allow more convenient and faster floating-point calculations in assembly language. An interface

board from Tecmar, Inc. was used to communicate with other external devices via 96 digital input and output lines. The IBM AT was chosen because of its computing power and the wide range of MS-DOS microcomputers which are compatible with the IBM, at least up to the hardware and software levels used in this project.

THE IMAGE PROCESSING ROUTINES

The image processing routines are designed to grab a frame from the camera, identify different parts in one image, and compute descriptors on the basis of the geometric shape of the parts. These descriptors are then compared with the values from pre-taught parts in order to recognize them. A user trains the system by simply presenting sample objects in all of their stable positions to the vision system. This allows the software to recognize parts that look different depending on the side from which they are viewed. These subroutines have been written in assembly code to ensure short processing times. They can be called upon from a high-level language such as BASIC to allow for easy user interface.

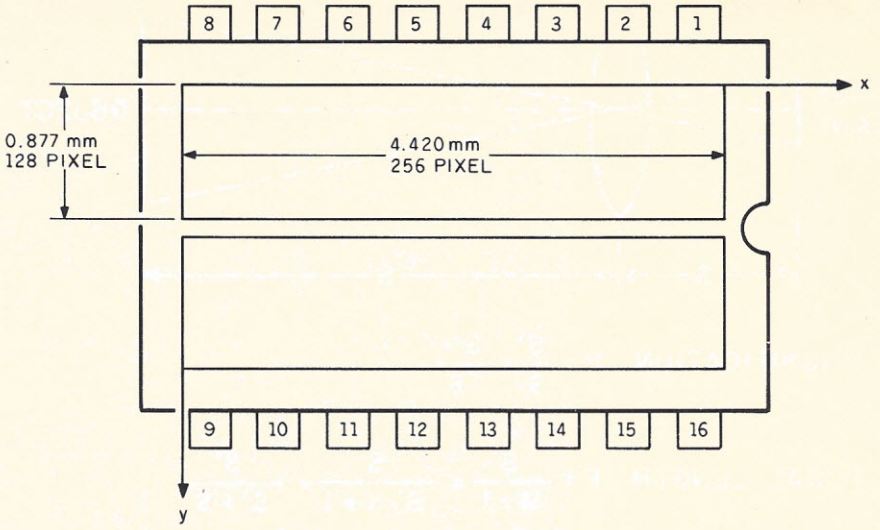


Figure 1. A problem in converting pixel to metric units lies in the differing camera resolution for the x and y axes. This results from the rectangular shape of the imaging chip and picture element.

The development of these routines was based on a connectivity analysis algorithm (3,5) used to create a so-called blob list. A blob is any group of connected pixels in a binary image. It is a generic term that includes both objects and holes as well as the background. This type of blob-finding algorithm was chosen for its short processing time because the desired blob list is generated in a single raster scan of the image (3,10). The implemented algorithm can be used to analyze binary images of various sizes. Because of programming constraints, the number of pixels per row is limited to 256.

A postprocessor computes the area, the centroid, the moments of inertia about the x and y axes, the first- and second-order

Advertising

R.S. No.	Company
48	AEG Corporation, Cov. II
30	Alpha Products, p. 23
31	American Grinding & Machine Co., p. 2
32	Ampro Computers, Inc., p. 33
33	BEI, Industrial Encoder Division, p. 7
34	Becker Publishing Co., Inc., p. 6
35	Bersearch Information Services, p. 34
36	Conco-Tellus, p. 35
37	CyberPak Co., p. 33
38	Dolan-Jenner Industries, Inc., p. 10
39	Helical Products Co., p. 6
49	Lord Corporation, Cov. IV
40	MESANDD Microprocessor Engineering, p. 31
42	MillerEdge, p. 9
*	North American Technology, Inc., pp. 27, 30, 36
*	1986 Sensor & Transducer Directory, Cov. III
43,44	Sensors Expo, pp. 18,19
45	Tapeswitch Corp. of America, p. 11
46	Vernitron Controls, p. 31
47	Wire Crafters, Inc., p. 9

* *Correspond directly with company*

THE JOURNAL OF INTELLIGENT MACHINES
ROBOTICS
ENGINEERING

Advertising Representatives
EAST and WEST

Brian R. Beihl
Associate Publisher
174 Concord St.
Peterborough, NH 03458
(603) 924-7136

MIDWEST

Don Ransdell
The Pattis Group
4761 West Touhy Ave.
Lincolnwood, IL 60646
(312) 679-1100

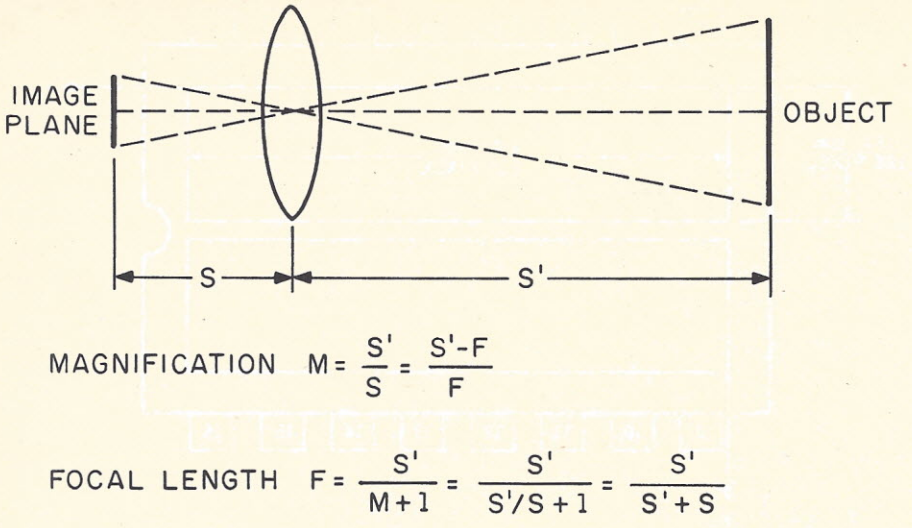


Figure 2. To find the actual object dimensions, two scaling factors are multiplied by the number of pixels in the x or y direction and by the lens magnification factor, computed using the above equation.

moments of invariant, and the number of holes from the blob list (10). The last three values are used by a third routine to compare a part against pre-taught models in order to find a match. These three values have been selected since they are independent of the part orientation in two-dimensional space.

The implementation of this vision system for a simple part-sorting application (11) demonstrated its feasibility. The major disadvantage was the distance dependency of the image information; that is, the same part will yield different characteristic data if it is analyzed from different distances. This limited the system's use for automation applications with one fixed camera location. This limitation was overcome with the addition of the sonic range-finding device. The characteristic image data can now be determined in metric units representing the actual dimensions of the part.

A problem in converting pixel to metric units lies in the differing camera resolution for the x and y axes. This results from the rectangular shape of the imaging chip (Figure 1). The scale factors are

$$\text{Scale}_x = 4.420/256 \text{ [mm/pixel]}$$
$$\text{Scale}_y = 0.877/128 \text{ [mm/pixel]}$$

Since every other pixel was used because of previously mentioned quality considerations, the actual scaling factors are

$$\text{Scale}_x = 4.420/128 \text{ [mm/pixel]}$$
$$\text{Scale}_y = 0.877/64 \text{ [mm/pixel]}$$

To find the actual object dimensions, multiply these scaling factors by the number of pixels in the x or the y direction and by the lens magnification factor, which is computed using the equation shown in Figure 2.

The processing times for this machine vision system are quite short if you consider that all image processing tasks are performed via software. The following execution times have been evaluated for an image containing one part of average complexity (e.g., 1 hole and 14 edges):

- **Connectivity algorithm.** 0.3 sec. for a 128 by 64 image. Since the processing time is directly proportional to the image size, a 128 by 128 pixel image would require 0.6 sec. processing time.
- **Postprocessor.** 0.2 sec. for the computation of the results and an additional 1.4 sec. for the output display. For applications where time is crucial, the display of the results can be omitted. This minimizes the processing time.
- **Library search routine.** 0.1 to 0.15 sec. for a part library containing 20 parts. The execution time of this subroutine depends on the part searched for and the number of different parts stored in the library since a brute force scanning routine is used to find a matching part.

CONCLUSIONS

The vision system can analyze up to 40 images/parts per minute. The image processing routines are designed to identify and recognize nonoverlapping geometric regular parts regardless of their orientation and distance from the camera. Note that the software does not depend on this specific hardware configuration. These routines could also be used to analyze binary images generated by other camera systems. The camera can operate in normal room lighting, but best results are achieved in a controlled light environment with no shadows and sufficiently high contrast between parts and background.

The low cost of this vision system makes it attractive for industrial applications for which a machine vision system is desirable but not economically feasible. The system can also be used for educational purposes to teach students the essential features as well as the advantages and limitations of machine vision.

REFERENCES

1. Keil, R.E. "Survey of Off-The-Shelf Imaging Systems." *Proceedings of The Third Annual Machine Vision Conference* (1984): 1–10.
2. Miller, R.K. *Intelligent Robots.* (Ft. Lee, NJ: SEAI Institute and Technical Insight Inc., 1983).
3. Cunningham, R. "Segmenting Binary Images." *Robotics Age* (vol. 3, no. 4, 1981).
4. Wilf, J.M. "Chain Code." *Robotics Age* (vol. 3, no. 2, 1981): 12.
5. Gleason, G., and G. Agin. "A Modular Vision System for Sensor-Controlled Manipulation and Inspection." *Proceedings, 9th International Symposium on Industrial Robots* (March 1979): 57.
6. Roth, S.D. "Recognizing Parts That Touch." *Robotics Age* (vol. 7, no. 6, 1985): 30.
7. Bolles, R. "Robust Feature Matching Through Maximal Cliques." *SPIE Technical Symposium on Imaging Applications for Automated Industrial Inspection and Assembly* (1979).
8. Wieland, C. "The MicroEye." *Byte* (vol. 8, no. 10, 1983): 316.
9. Ciarcia, S. "An Ultrasonic Ranging System." *Byte* (vol. 9, no. 10, 1984).
10. Petersen, V., and J. Even. "Microcomputer-based Binary Vision System." Accepted for publication in the *Journal of Applied Engineering Education.*
11. Petersen, V. "A Microcomputer-based Binary Vision System." MS Thesis (Iowa State University, 1985).

Volker Petersen is a Graduate Research Assistant and John C. Even, Jr. is a Professor in the Department of Industrial Engineering at Iowa State University.

Reader Feedback

To rate this article, circle the appropriate number on the Reader Service card.

6	16	26
Excellent	Good	Fair

Edited by Stephanie vL Henkel

AT ROBOTS 10

Robots 10, held April 21–24 in Chicago, brought with it a number of surprises. Attendance was one of them—down to 17,221 from last year's 19,480 who trouped through Detroit's Cobo Hall, a less classy structure than McCormick Center but closer to most of the robotic action in this country. The show is scheduled for Chicago again next year, but there is talk of doing away with a yearly centralized event in favor of a biennial convention alternating with Robots West and Robots East.

There was some grumbling among the exhibitors (228, as opposed to last year's 265) about the number of attendees, but at the same time they described the visitors as being of "better quality." The term seemed to signify that most of the showgoers wore suits and asked informed questions about prices and systems approaches—in other words, they were sales prospects. Some big names were missing: PRAB, American Cimflex (formerly American Robot), Cybotech, and GE. Automatix was there, but just barely. The exhibit space did not go begging, however; GMF Robotics occupied 7750 square feet of the floor with seven CIM-connected workcells. In one of them sat an AGV that announced GMF's entry into that market via an agreement with Eaton-Kenway.

Speaking at the opening press conference, Eric Mittelstadt, the new president of Robotic Industries Association and also president and CEO of GMF Robotics, said the leveling-off of the industry forecast by some observers "is not an element that should surprise or discourage us at all. The forecasts of a 'nuclear explosion' made in 1982 didn't come out of the industry itself, so comparisons should not be made with those numbers." The automotive share of the market is, however, expected to decline and the new target industries are medical, tobacco, chemical, beverage, food, and packaging, Mittelstadt said.

RIA is in the process of reexamining its 1974 definition of "robot," and Mittelstadt tipped the organization's hand a bit when he said in his concluding remarks that "robots are not just reprogrammable manipulators anymore; they are systems with vision, tactile sensing, intelligence, etc." The customer, he said, "now wants systems and not just robots."

Charles Bernard and Lee Holcomb also spoke, addressing their remarks to the coming role of robots in aerospace and the military. Bernard, director of Land Warfare, Office of the Undersecretary of Defense for Research and Engineering, described fiber optics and artificial intelligence as the "key technologies" for developing the teleoperated remote presence vehicles for which the military will be spending $10 million in R&D funds. Robotics will change the face of warfare, Bernard said, but the conflicts of the future will not be machine against machine, without regard for the number of robots destroyed. Someone will always have to account for every weapon assigned to a unit, he said, and it will be very important to account for AGVs with high price tags. "Humans," he said, "will continue to be part of any war that gets started. Wars won't get any easier because of robots. They will still be horrible."

Holcomb, the director of Information Sciences and Human Factors Division of the NASA headquarters in Washington, DC, envisioned robots as increasing mission safety by replacing humans in extravehicular activity in space. NASA's current investment of $30 million will grow, he said, to $40–$50 million next year.

Robert Day, an engineering associate of Applied Technology Organization of Eastman Kodak and the newly installed president of RI/SME, contributed to the conference surprises by declaring that "hydraulics are on the way out," a remark not lost on Walter Weisel, president of PRAB Robots and retiring president of RIA. At a subsequent press conference of his own, in which PRAB introduced two new electrohydraulic heavy-duty robots, Weisel said he perceived Cincinnati Milacron and Unimation as "backing out of the hydraulic market," but added that he saw a "great growth" in that market for accuracy in applications requiring a 4000 to 6000 pound payload capacity.

Weisel had his own surprise in store for us: when he described a vision-guided system his firm had recently installed for a "major automotive manufacturer," he named the company—General Motors. Briefly stated, the system observes a 50-foot tractor trailer truck coming to the receiving dock with bench seats for a GM van, calculates the position of the seats (preloaded by color), unloads them onto monrails, and delivers them to the points of assembly. PRAB's announcement that it was entering the low-cost vision market, Weisel said, led to a stock jump of 21 percent in three hours; the vision systems are priced at under $10,000 and can be added directly to PRAB's robots.

On the convention floor, we found that the welding and water jet cutting robots of last year had for the most part been replaced by sealant applicators, material handlers, and assembly devices. At the KUKA booth (where we learned that the company name was created from the surnames Keller und Knappisch) we watched massive orange robots assembling a car, using the three proximity sensors in its end effector to calculate where to place the doors. ASEA's pendular robot, also large and orage, assembled a 1/14th scale model of itself every 30 seconds. A Seiko Accusembler robot at the Kanematsu-Gosho display wrote its own name in a sealant compound and drew recognizable pictures of Snoopy. In another booth, an Autonetics SR800 robot traced automobile headlight outlines in black adhesive onto a scroll of paper and then drew three geometric patterns of a fair degree of complexity.

We saw also a prototype safety device being developed by Mechanotron. The principle was an array of pressure sensors placed above a robot's wrist and covered with a flexible rubber "skin." When a human operator squeezes this "forearm," the robot shuts

down. At Adept Technology we were introduced to the world's first task-level programming system, AIM, that will let the applications programmer define high-level instructions for the robotic workcell's tasks. All the cell operator will need to do is specify task sequence. Finally, we saw Igrip (interactive graphic robot instruction program), a remarkable CAD, or, more correctly, CAAP (computer aided automation planning) system being demonstrated by Deneb Robotics Inc. Igrip can be used to build a robot and to simulate its movements in wire frame, solid modeling, and in a third, see-through mode its creators call "transparency." Igrip also simulates automatically, in real time and in bright red, potential collisions between two robot arms and between a robot and a stationary object. The system's developers anticipate applications in off-line robot programming.

MARKET RESEARCH

The **Robotic Industries Association** has released a new set of statistics, the result of changes in reporting methods. The current numbers can be summarized as follows: U.S.-based suppliers shipped 6209 robots valued at $442.7 million in 1985, a 21 percent increase in units and a 33 percent increase in dollar value over 1984's 5136 units at $332.5 million. RIA estimates a U.S. installation of over 20,000 robots at the end of 1985; about 50 percent are in the auto industry, with the electronics, off-road vehicle, aerospace, and home appliance industries among the other leading end users. A total of 1656 units valued at $142.8 million were shipped in the fourth quarter of 1985, up from 1503 units at $97.6 million in the fourth quarter of 1984. The backlog of unfilled orders stood at 2287 units, $247 million at the end of 1985. New orders for the year totalled 6747 units at $483.2 million, an increase in units over 1984's 6045 but down in dollar value from the $501.1 million mark set in 1984.

ORGANIZATIONS

► **Otto Renius** has been appointed president of the **Michigan Automated Vehicle Research Consortium**. The organization is a cooperative effort between Michigan's businesses and universities to combine vehicle research and development with automation technology to address Department of Defense needs.

► The **Industrial Technology Institute**, the nation's largest organization dedicated exclusively to advanced automated manufacturing technologies, has appointed **Dr. James C. MacBain** director of its Flexible Machining Laboratory. Formerly manager of the lab's Sensors and Machine Control Group, MacBain replaces Dr. Donald R. Falkenburg, who became vice president for Research and Development last year.

CALLS FOR PAPERS

Robotics International of the Society of Manufacturing Engineers will accept abstracts until July 15 for the Robots 11/17th International Symposium on Industrial Robots to be held April 26–30, 1987 in Chicago, Illinois. Topics include robotic applications, R&D, human factor considerations, and robotic education. For a submission form or further information, contact Mike Tew, SME, Technical Activities Dept., One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500, ext. 359.

The **1987 International Computers in Engineering Conference** will focus on the development, application, and research of computers in mechanical engineering. Abstracts are due by October 15. Contact Dr. Ramjee Raghaven, Conference Chair, Foster Wheeler Development Corp., 12 Peach Tree Hill Rd., Livingston, NJ 07039, telephone (201) 533-3518.

CORPORATE NEWS

► **Lab-Volt** has acquired **Cybot, Inc.**, the former manufacturer of the Tutor™ robot, a modular, reconfigurable robot system for technical education. Lab-Volt will market an enhanced version of the robot as part of its line.

► **Odetics, Inc.** has received a contract for nearly $50,000 from **NASA** to develop a multiple robotic arm system. The initial system will feature two seven-axis manipulators controlled simultaneously by a single control input so an object jointly held by the arms is carried through the desired spatial path. Future uses are expected to include space station and satellite servicing and maintenance, as well as operations involving hazardous substances.

► **Litton's Industrial Automation Systems** group has announced two contracts: **General Motors** of Canada will spend $11.2 million for five overhead monorail delivery systems for its Oshawa, Ontario body and assembly plant. **Brylane**, a division of The Limited, has ordered a computer-controlled conveyor system valued at "several million dollars" to be installed in its national distribution warehouse in Indianapolis, Indiana.

► **WT Automation, Inc.** has received two contracts from **Boeing Military Airplane Company** to design and build three robotic workcells based on Adept assembly robots, an IRI vision system, and various customized cell components. Two of the systems will automate the testing and storage of electronic devices and the third will automate lead forming and verify part numbers of components used by BMAC.

► **Veeco Instruments** has signed a definitive agreement to acquire for cash **Modular Power Systems, Inc.**, subject to the approval of Modular Power's shareholders and certain other conditions. The firm designs and manufactures military power supplies.

In The Robotics Age™

► **GMFCanada**, established last November as a wholly owned subsidiary of GMF Robotics, has opened a new headquarters in Mississuaga, Ontario. The facility houses the firm's marketing operations, training and demonstration areas, a lab, and a systems assembly area. GMF's sales in Canada last year represented a 58 percent share of the market.

► **Weldun International** has announced the formation of the **AutoNetics Division**, which will offer a line of pre-engineered, pre-manufactured small parts handling and assembly modules.

► **Accuratio Systems Inc.** has received a $1.3 million contract from **Fisher Guide Flint Manufacturing**, Chevrolet Motor Division, General Motors Corporation to design, develop, and manufacture a complete robotic system for the automatic production of a sheet molding compound grill outer panel assembly in GM's 1988 "W" car. The system's 13 integrated workstations will feature ASI's gantry robots and Allen-Bradley controllers.

► **CAMCO**, the Commercial Cam Division of Emerson Electric, has formed a robotics department to develop, market, install, and service the firm's new line of Auto Load™ machine tool loading robots. The department will also market the Cambot line of pick and place devices.

► **American Cimflex Corporation**, formerly American Robot Corporation, has acquired **Logitek Inc.**, a manufacturer of advanced control products and systems for the factory floor.

► **Adaptive Intelligence** has announced a reorganization in which Dave Burwen replaced Donald Pedrotti as the firm's president and CEO. Pedrotti, a founder and co-developer of the company's core technology, became chairman of the board responsible for strategic planning and acquisitions for the company.

► **Burroughs Corporation** is proposing to merge with **Sperry Corporation** by acquiring 100 percent of Sperry's common stock for $70 per share to be paid in cash and securities. The merger would create the world's second-largest computer company and one of the nation's major suppliers of defense-oriented systems and services, according to Burroughs Chairman W. Michael Blumenthal.

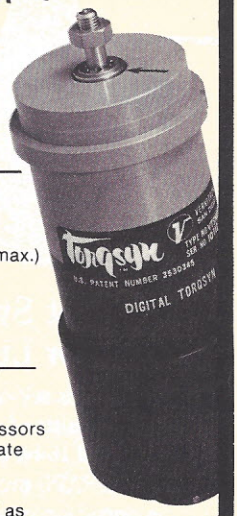
► **XTAL Corporation** has announced a corporate restructuring and a marketing agreement with **Cincinnati Milacron**. Co-founder John Titus has been named president and CEO, replacing co-founder Kendell E. Johnson, who also resigned as a director and has accepted the position of management consultant to the firm. Bert B. Locke has replaced Paul Morrow as VP of sales, and Robert J. Williams was elected VP of engineering. The company has instituted an across-the-board salary reduction and employee stock option compensation program. Under the terms of XTAL's agreement with Milacron, that firm will purchase and offer to its customers XTAL's FACTORYnet® system.

DIGITAL Torqsyn®

REMOTE POSITIONER

MODEL VTSND23-P2

Microprocessor compatible, self-contained closed loop servo



Features

- 8 and 16 bit input
- 10′ accuracy
- Requires only ± 15 VDC power supply
- Continuous rotation, 400 rpm slew rate (max.)
- TTL or CMOS compatible
- Available in sizes 15, 23, 31 and 37, analog or digital mode
- Available torques from 2.5 to 100 oz.-in.

Applications

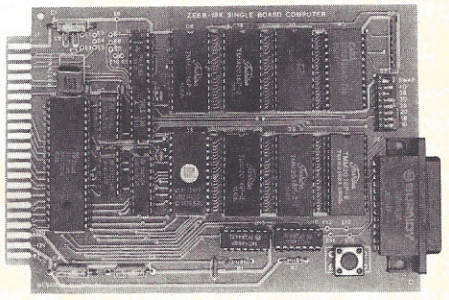
- Oil exploration
- Robotics
- Component testing
- Machine tools with on-board microprocessors
- Industrial processing to power and activate relays, switches, valves, etc.

Also available with 16 bit digital output and as analog units utilizing synchro or resolver input.

Call or write today for additional information or application assistance.

Vernitron San Diego
A Division of Vernitron Corporation
1601 Precision Park Lane
San Diego, CA 92073
Tel. 619-428-5581
TWX: 910-322-1862

ZEE8-18K I/O CONTROL COMPUTER COMBINES PROGRAMMING EASE OF BASIC WITH THE DISK-LIKE STORAGE OF AN EEPROM FOR ONLY $239!

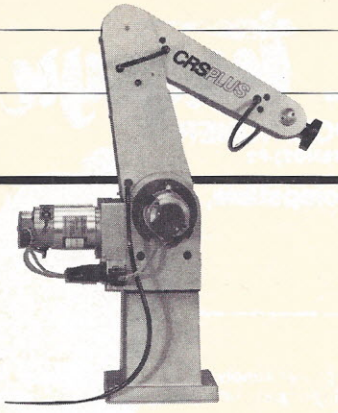


The **ZEE8-18K** SBC combines the funtions of computer + I/O board + EPROM writer + EPROM eraser—**without** the UV light and additional power supply needed for erasing and writing EPROM's. With an endurance of 10,000 write cycles per byte and the ability to erase/write **single bytes**, the EEPROM can be used like a disk. Programs can be stored in tiny BASIC or Z8 hex code and will autostart after flipping an on-board DIP switch.

2K BASIC interpreter, 12K CMOS RAM, 2K monitor EPROM, 2K EEPROM, 32 I/O lines, 2 counter/timers, RS-232C port.

MESANDD Microprocessor Engineering
1509 Francis Street, Albany, CA 94706
(415) 526-5155

New Products



Small Robot System Is Designed for Light Handling

The CRS Plus self-contained small robot system consists of a five-axis articulated arm, a dedicated 16-bit controller, teach pendant, and the RAPL programming language. It was developed for automating tasks such as handling small parts, materials, and light tools, or for sample preparation in laboratories. The robot has a 4.4-lb. payload, a ±0.005 in. repeatability, a 22-in. reach, and speeds up to 40 in./sec. Options include three additional axis control cards, video terminal, PC interfaces, and pneumatic or servo grippers.

For more information, contact: Ray Simmons, CRS Plus, Inc., 2114 Junction St., PO Box 163, Station A, Burlington, Ontario, Canada L7R 3Y2, telephone (416) 639-0086. Circle 100

Device Replaces Breakaway Joints Between Robot and End Effector

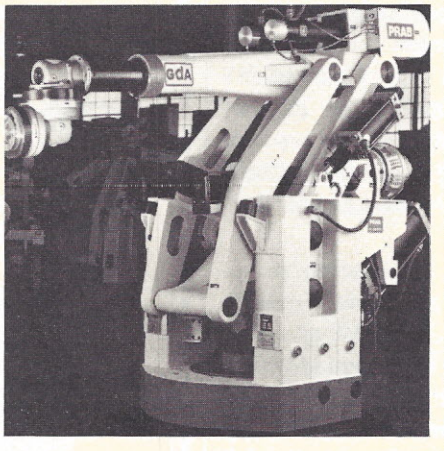
The new Model D-4421 Uni-Coupler can handle dead loads of up to 170 lb., including tooling and part. The safety joint is activated by downward side-loading and downward movement of the robot arm, as well as lateral, forward, and backward motion. It does not break, but allows continued travel up to 15 degrees of arc after shutting off the machine. In most cases, after the end effector returns to the normal position the robot can continue operating. The D-4421 responds to a minimum of 250 in.-lb. through a maximum of 1400 in.-lb. side-loading pressure, with an infinitely variable response between these settings. An optional outrigger permits upgrading or downgrading of robot sensitivity to correspond to materials being handled.

For more information, contact: Robotic Accessories, 4191 US Route 40, Tipp City, OH 45371, telephone (513) 667-5705. Circle 101

Welding and Cutting Robot Offers Short Setup, Training Time

The MAC 500 is a five-axis (four simultaneous, one independent) articulated SCARA system, specifically designed for precision welding or cutting of close tolerance parts in both moderate (100–500 pieces) and long-run production. It can be set up in less than one day, programmed by anyone with welding and/or cutting experience in less than 15 minutes, and requires less than a day of training time. Operating speeds range from 2.4 to 2362 in./min., and cutting speeds are up to 400 in./min. Repeatability is ±0.004 in., and accuracy is ±0.008 in. The system can handle gas metal arc, flux core arc, and gas tungsten arc welding.

For more information, contact: ESAB North America Inc., PO Box 2286, Ft. Collins, CO 80522, telephone (303) 484-1244. Circle 102



Versatile Robot Performs Eight Axes of Motion

A new electric-drive servo-controlled articulated arm features a five-link kinematic design that makes it suitable for heavy parts handling, water jet cutting, and spot welding. The G-46 is capable of eight simultaneous axes of motion, including traverse base and/or positioning table. It has a 220-lb. payload at maximum speed and at full extension. Maximum horizontal reach is 119 in. from center line to faceplate. Repeatability is ±0.025 in.

For more information, contact: Richard Clendenen, National Sales Manager, PRAB Robots, PO Box 2121, Kalamazoo, MI 49003, telephone (616) 329-0835. Circle 103

Conveyor Firm Introduces Palletizing Robots

After 75 years in the palletizing business, Alvey Inc. has entered the robot business with the Skilled 602 and 502. The 602, an all-electric articulated robot, features a four-axis DC servo drive system that allows 330 degrees of rotation for both arm and gripper. It is designed for heavy tasks carried out over long periods of time and rated at six complete cycles/min. The 502 is a cylindrical robot, suited to slower operations of up to five standard palletizing operations/min. Depending on gripper style, both robots have a load height capacity of 54 to 78 in.

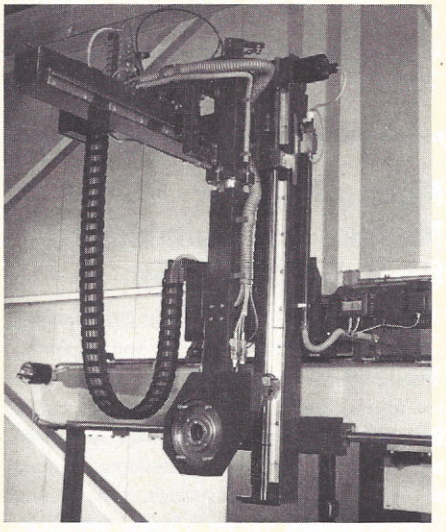
For more information, contact: Alvey, Inc., 9301 Olive Blvd., St. Louis, MO 63132, telephone (314) 993-4700. Circle 104

New Products

Parts Removal Robot Features Shop Floor Programming

Programming for the Meister plastic injection molding parts removal robot is simplified by having the computer lead the operator through the most efficient programming sequences. Further, because the Teach and Learn computer is a freeform system, subsequent programming changes need not be made as part of a specific sequence. During programming, the computer ensures that all safety interlocks are properly initiated. The computer also includes a complete self-diagnostic system; if the robot fails, the CRT displays a message in English stating the precise location of the problem.

Other features of the Meister system include quick change tooling, gentle parts handling, a fast-action vacuum system, and an optional 180 degree arm rotation to permit parts removal from either a moving or a stationary platen. The



Meister is available for presses ranging from 500 to 3000 tons clamping capacity.

For more information, contact: Martin Industries, 100 Bowles Rd., Agawam, MA 01001, telephone (413) 789-1990. Circle 105

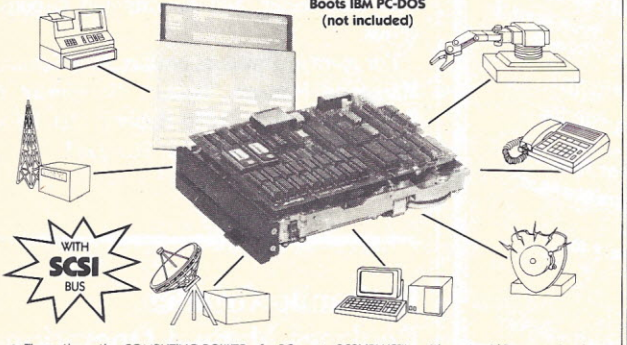
Clean Room Robot Automates Compact Disc Production

Designed to meet clean room specifications, the AAC/Sailor robot system removes compact discs from the mold, and stacks or palletizes them for subsequent processing. The side entry parts removal robot positively removes the disc and runner from the mold and loads them into a magazine stacker. The robot can also thread the disc onto pins on a downstacking rotary indexing table. Compliant vacuum fixtures and silicone vacuum cups are used to remove the disc without damaging its surface, and mechanical grippers with sensors remove the runner and dispose of it during traverse back to the mold area.

For more information, contact: Terri E. Ohryn, Marketing Coordinator, Automated Assemblies Corp., 25 School St., Clinton, MA 01510, telephone (617) 368-8914, ext. 362. Circle 106

Little Board™/186....$495

High Performance, Low Cost PC-DOS Engine



- Three times the COMPUTING POWER of a PC
- Data and File Compatible with IBM PC, runs "MS-DOS generic" programs
- 8 MHz 80186 CPU, DMA, Counter/Timers, 128/512K RAM,zero wait states, 16-128K EPROM
- Mini/Micro Floppy Controller (1-4 Drives, Single/Double Density, 1-2 sided, 40/80 track)
- 2 RS232C Serial Ports (50-38, 400 baud), 1 Centronics Printer Port
- Only 5.75 x 7.75 inches, mounts directly to a 5-1/4" disk drive
- Power Requirement: +5VDC at 1.25A; +12VDC at .05A; On board -12V converter
- SCSI/PLUS™ multi-master I/O expansion bus
- Software Included:
  - PC-DOS compatible ROM-BIOS boots DOS 2.x and 3.x
  - Hard Disk support
- OPTIONS:
  - Expansion board with:
    - 128 or 512K additional RAM
    - 2 Sync/Async RS232/422 serial ports
    - Battery backed Real Time Clock
    - 8087 Math Co-Processor
    - Buffered I/O Bus
  - STD Bus Adapter
  - Utilities source code
  - TurboDOS / Networking

IBM®, IBM Corp.; 80186®, Intel, Corp.; Turbo DOS®, Software 2000, Inc.

AMPRO COMPUTERS, INCORPORATED

67 East Evelyn Ave. • Mountain View, CA 94041 • (415) 962-0230 • TELEX 4940302

Circle 32

16 Axis Step Motor Control Performance/Cost Break-Through

Cyberpak's BIPOLAR CHOPPER technology provides 2-5 times the performance of simple circuits. No external power resistors are required.

Complete 4 axis systems w/IBM-PC interface, including control system software (RBCS BASIC), at under $1000. Driver modules start at $89.50/axis.

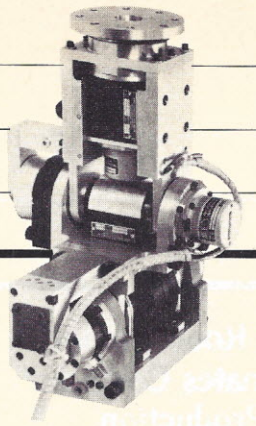
CyberPak company

P.O. BOX 38 ■ BROOKFIELD, IL 60513 ■ 312/387-0802

MC/VISA OEM and Distributor Pricing Available

Circle 37

New Products



Direct Drive Wrist Provides a Final Three-axis Motion for Robot Arm

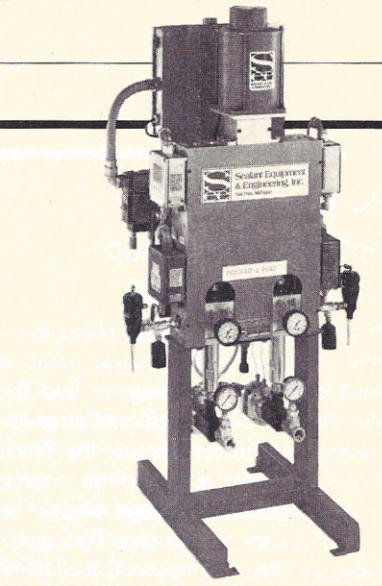
The Hyd-ro-wrist® is a compact assembly of three hydraulic rotary actuators supported on prelubricated roller bearings to provide final three-axis motion for robot arms. Featuring servo valves mounted directly on internally ported brackets to ensure smooth action with zero backlash, models are available with payload capacities of 50, 120, and 300 lb. Mounting requires four bolts and two hydraulic hose connections. There is no axial or radial loading on the actuators, and all internal parts are enclosed and sealed. The modules operate at 2250 psi maximum pressure and weigh 63, 125, and 250 lb.

For more information, contact: Daniel Collins, Mktg. Services, Bird-Johnson Company, Fluid Power Div., 110 Norfolk St., Walpole, MA 02081-9986, telephone (617) 668-9610. Circle 107

Motion Detector Modules Are Suitable for Robot Navigation

The new models GOS2578/79/81 pulsed motion detector modules from Alpha Industries' Semiconductor Division feature very low average current drain (1.3 mA is typical), 9 V operating voltage, and high sensitivity and reliability. Other specifications include 9.47–10.7 GHz frequency range, cavity ground negative polarity, 1 percent typical duty cycle, and 20 μs typical pulse width. The units are designed to meet FCC regulations.

For more information, contact: Alpha Industries, Inc., 20 Sylvan Rd., Woburn, MA 01801, telephone (617) 935-5150. Circle 108



Programmable System Allows Automatic Dispensing of Various Adhesives

The Program-A-Bead II™ works with robotic or gantry-style generating systems to dispense a uniformly mixed material bead over a complex path without having to maintain constant speed. It can be programmed to automatically vary material flow rate, and bead uniformity on a part can be maintained at speeds up to 2000 in./min. Included in the system are an electric motor, two positive displacement metering cylinders, dynamic power mixer with tachometer, and nondripping dispense valves.

For more information, contact: Nick Schultz, Marketing Manager, Sealant Equipment & Engineering, Inc., 21000 Hubbell, Oak Park, MI 48237, telephone (313) 967-2111. Circle 109

Hydraulic Grinder Replaces Manual Operations

A new grinder designed for use with robots develops as much as 20 hp, uses a 3 by 60 in. abrasive belt, and weighs less than 100 lb. Among the advantages it offers are increased production because of the greater pressure applied at the point of grind, improved finish quality, better consistency from piece to piece, programmability to follow a contour, and reduced worker-related problems.

For more information, contact: Clarence Grelle, V.P., G & P Machinery Corp., 2801 Tobey Dr., Indianapolis, IN 46219-1419, telephone (317) 898-0750. Circle 110

EVERYTHING YOU NEED . . . $279.00

Now it's easy to program the Heath-Zenith HERO-1® Robot with an Apple® II. HERO® Macros for the S-C Software 6800 Cross Assembler program in Heath's Robot Interpreter Language with easily remembered mnemonics. [For example, the line: 1130 > MVWRIM GRIP, OPEN, 60, FAST instructs the HERO® to open his gripper 60 units at fast speed. Motor position is expressed in base-10.]

The HERO® Macros come with 30 pages of documentation. Transfer to HERO® with ROBI . . . an affordable interface for the robotics experimenter . . . is simple.

- ROBI is a complete package. No additional hardware required for Apple® or HERO®.
- ROBI installs quickly in an Apple® II, II+, or IIe. Once installed, no hardware changes are needed. Within minutes, you will be programming HERO®.
- With ROBI and the Cross Assembler, the programmer uses Apple®'s memory to write the program, and HERO®'s memory to run the program.
- Not "copy protected," archival copies may be made as needed.
- ROBI offers expansion potential.

VISA and MasterCard accepted.

BERSEARCH Information Services
26160 Edelweiss Circle
Evergreen, Colorado 80439

The Cross Assembler with HERO® Macros sells for $100.00; the ROBI Interface sells for $199.00. Both as a package — $279.00.

To order, or for more information, call (303) 670-6137.

APPLE® is a trademark of Apple Computer HERO® is a trademark of Heath Electronics

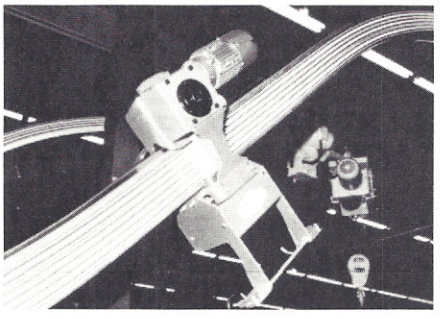
Circle 35

New Products

"Smart" Monorail Frees Floor Space

The Automatic Monorail System consists of a large number of individually powered and controlled trolleys running on a specially designed overhead rail. The rail design transmits electrical power and control signals to each trolley. Multiple trolleys can be started, run at dissimilar speeds, and stopped completely independently from the motions of any other trolley. Positioning accuracy is less than ± 0.125 in. The trolley can climb and descend slopes, permitting greater factory layout flexibility. Payloads are up to 6000 lb.

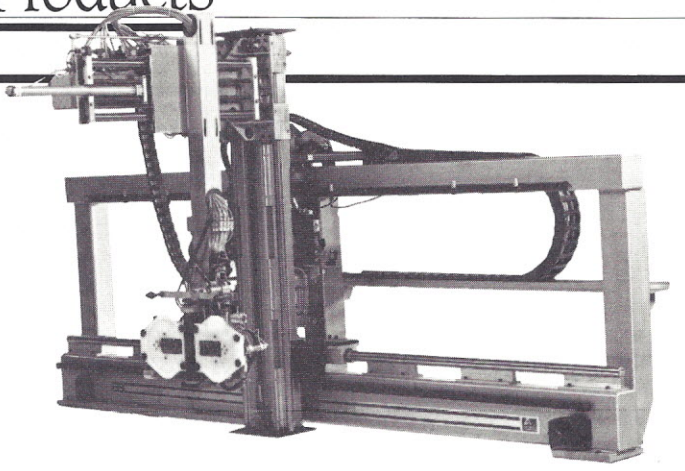
For more information, contact: Mobot Corporation, a subsidiary of Advanced Manufacturing Systems, Inc., 1880 Dairy Ashford, Houston, TX 77077, telephone (713) 558-1808. Circle 111



Automated System Delivers and Removes Component Trays

The A.T.S. tray system is designed to handle electronic components and small parts that cannot be fed and oriented in standard industry packaging. The feeder automatically delivers trays of components to a precisely fixed location within the robot's work envelope, removes empty trays, and replaces them with full trays. Several loaded trays can be stored in the magazine. The feeder is controlled via a PLC or computer with "step forward" and "step back" push-button control, allowing single-step operation for debugging procedures.

For more information, contact: Calvin Read, Marketing Manager, Automation Tooling Systems Inc., Chicago Regional Sales Office, 175 Olde Half Day Rd., Lincolnshire, IL 60069, telephone (312) 948-7374. Circle 112



Robot Systems Strip Parts from Molding Machines

The Tital series robots, designed for 500–4000 ton molding machines, can be programmed for a virtually infinite range of rectilinear motion sequences and can strip parts from stationary or moving molds. Two of the three Titan models feature three linear and three rotary axes, all riding on linear bearings for maximum speed and support. Speed adjustments are via air flow controls and proximity sensors limit travel. The frame mounts to a large area of the stationary platen to reduce in-mold vibration. A C-90 wrist rotation/grip circuit extends handling versatility. Specialized grippers are also available.

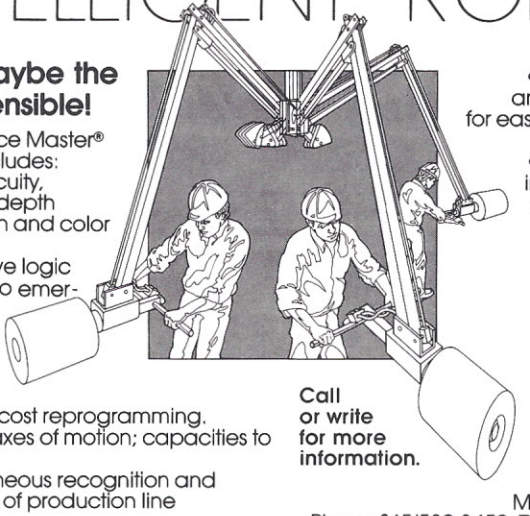
For more information, contact: Tony Mass, General Sales Manager, Application Automation, Inc., an AEC Company, 850 Pratt Blvd., Elk Grove Village, IL 60007, telephone (312) 593-5000. Circle 113

The Conco Balance Master:®

THE WORLD'S MOST INTELLIGENT "ROBOT"...

and maybe the most sensible!

The Balance Master® System includes:
- Visual acuity, including depth perception and color resolution.
- Deductive logic response to emergencies.
- No initial programming costs and instant no-cost reprogramming.
- Up to 7 axes of motion; capacities to 1,700 lbs.
- Instantaneous recognition and correction of production line problems.



- Low cost tooling and flexible design for ease of task/location modification.
- Simple, low cost installation — immediate start-up.

For more information on the Conco Balance Master System, circle the reader service number below, or write: Industrial Manipulator, Conco-Tellus, an Interlake Company, Mendota, IL 61342. Phone 815/539-3450. TWX 910/642-1733.

Call or write for more information.

CONCO-TELLUS
An Interlake Company

Dealer Inquiries Invited

Circle 36

New Products

Laser Protection Lenses Are Available as Spectacles

The Glendale 2500 series Laser-Gard® lenses, an established standard for laser-protective eyewear, are now offered in the form of spectacles for use in hazardous environments. Eight radiation absorbers are available for both narrow- and broad-spectrum protection against reflected radiation from eight different types of lasers. The absorbers are uniformly dispersed throughout impact-resistant polycarbonate lenses to ensure that accidental scratches do not degrade radiation protection. Additional safety is provided by a scratch-resistant coating and by the tripod configuration the spectacles form when laid down, keeping the lenses off the surface onto which they have been placed. The 66-mm lenses and sideshields afford total protection and eliminate tunnel vision.

For more information, contact: Glendale Protective Technologies, Inc. (an American Cyanimid subsidiary), 130 Crossways Park Dr., Woodbury, NY 11797, telephone (516) 921-5800. Circle 114

Vision System Prevents Population of Defective Boards

The QuadVu, available as an option on two newly introduced assembly systems, can also be installed on earlier Quad Model QS-34 pick and place assemblers. As boards arrive at the first assembly station, they pass beneath a video camera mounted on the assembler head. QuadVu looks first for a "reject" marker placed on a sector of a multi-image board by a technician or automatic inspection system. When a marker is detected, the board is bypassed for the rest of the assembly process.

The system also automatically adjusts the assemblers to compensate for tolerance variations in board fabrication and printing. During fabrication, small markings, or "vision targets," are etched with the circuit pattern. QuadVu inspects for these targets and compares their actual locations with position coordinates stored in the assembler's memory. If a difference is found, the system adjusts the assembler program to compensate.

For more information, contact: Quad Systems Corp., Marketing Dept., Two Electronic Dr., Horsham, PA 19044, telephone (215) 657-6202. Circle 115

Robotics Engineering Reprints!

Reprints of articles can be ordered in large quantities for:

• Trade show distribution • Promotional mailings • Educational programs • Media kits • Publicity releases

BLACK AND WHITE 8½" x 11" REPRINT PRICES

	500	1,000	3,000	5,000	7,000	10,000
2 PAGE	$120	$164	$249	$375	$501	$572.50
4 PAGE	$236	$320	$492	$744	$993	$1142.50
8 PAGE	$488	$680	$1089	$1872	$2238	$2582.50
10 PAGE	$708	$988	$1572	$2403	$3222	$3717.50

(PRICES DO NOT INCLUDE REPASTE AND SHIPPING CHARGES)
(5-6 Weeks Delivery Required)

Contact: Lorraine Cleveland
Robotics Engineering
174 Concord St.
Peterborough, NH 03458

* Priority (rush) orders are available at 35% above the prices listed above.
* Call for COLOR REPRINT prices!

1,000 SENSOR PRODUCT SOURCES

The 1986 Sensor and Transducer Directory

Now you can locate nearly 1,000 suppliers of sensor and transducer products in a single publication. The *1986 Sensor and Transducer Directory*, from the publishers of Sensors magazine, lists nearly 1,000 companies producing over 400 types of sensors and transducers. The *1986 Sensor and Transducer Directory* provides a comprehensive list of suppliers for each sensor category. Each company listing includes the company address, key personnel, and the sensor and transducer products available. For further information, an optional company/product line profile is also provided.

If you're looking for sensors, don't waste valuable time paging through catalogs and spec sheets. Join the thousands who have sensor sources at their fingertips—in the *1986 Sensor and Transducer Directory*. Order yours today!

ONLY $49.95

☐ Please send _____ copies of the **1986 Sensor and Transducer Directory** at $49.95 in the U.S., $51.95* in Canada, or $59.95* other foreign countries (includes postage and handling costs).

Payment Enclosed $ _____ ☐ Cash ☐ Bill Me PO# _____

☐ Personal Check ☐ MasterCard ☐ Visa

Account No. _____ Expires _____

Signature _____

Name _____ Phone _____

Company _____

Address _____

City _____ State _____ Zip _____

Send to **North American Technology** 174 Concord St., Peterborough, NH 03458 (603) 924-7261

*U.S. funds drawn on a U.S. bank

7/86 RE

INDUSTRIAL EVOLUTION

The need for greater productivity and higher profitability has created a *new age* of changing industrial technologies. **LORD Industrial Automation** is dedicated to using our technical leadership in tactile sensory technology to provide flexible solutions to today's production problems.

Tactile Sensing can help give your robots the flexibility you paid for. The ability to "Feel", "Handle", and "Manipulate" objects adaptively is important to automated assembly operations.

The **Lord F/T Series** wrist sensing system provides six axis force/torque sensing. The sensors provide information to allow adaptive control of robot motion based on monitoring the forces and torques between the robot and its environment. This information can be used to help determine the position of inadequately located parts or to verify when pre-programmed forces in assembly operations have been reached. Each system consists of a sensor, data pre-processor, controller and software, available in a range of force/torque capacities suited to your applications.

Applications Include:

- Controlled insertion of electronic components
- Gear assembly
- Force-controlled grinding
- Detection of parts contact or build-up of forces
- On-line inspection of mating forces in connectors
- Close tolerance robotic assembly

For more information on how **LORD Tactile Sensors** can help your robots evolve to become more flexible producers, call or write LORD Corporation, 407 Gregson Drive, Cary, NC 27511. Telephone: (919) 469-2500. Or use our toll-free number, 1-800-328-1305. Ask for one of our Application Engineers.

Circle 49

LORD Industrial Automation